

Weed management in organic agriculture: are we addressing the right issues?

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Summary

Despite the serious threat which weeds offer to organic crop production, relatively little attention has so far been paid to research on weed management in organic agriculture, an issue that is often approached from a reductionist perspective. This paper aims to outline why and how this problem should instead be tackled from a system perspective. Compared with conventional agriculture, in organic agriculture the effects of cultural practices (e.g. fertilization and direct weed control) on crop:weed interactions usually manifest themselves more slowly. It follows that weed management should be tackled in an extended time domain and needs deep integration with the other cultural practices, aiming to optimize the whole cropping system rather than weed

control *per se*. In this respect, cover crop management is an important issue because of its implications for soil, nutrient, pest and weed management. It is stressed that direct (physical) weed control can only be successful where preventive and cultural weed management is applied to reduce weed emergence (e.g. through appropriate choice of crop sequence, tillage, smother/cover crops) and improve crop competitive ability (e.g. through appropriate choice of crop genotype, sowing/planting pattern and fertilization strategy). Two examples of system-oriented weed management systems designed for organic agriculture are illustrated as well as future perspectives and problems.

Keywords: allelopathy, biodiversity, cover crops, cultural weed control, system approach, weed prevention.

Introduction

Weeds are often recognized as the most serious threat to organic crop production (Penfold *et al.*, 1995; Stonehouse *et al.*, 1996; Clark *et al.*, 1998), and fear of ineffective weed control is often perceived by farmers as one of the major obstacles to conversion from conventional to organic farming (Beveridge & Naylor, 1999).

Despite this, researchers have so far paid relatively little attention to weed management-related issues in organic agriculture. Furthermore, weed management is often approached from a reductionist perspective, e.g. focusing only on the comparison between types and adjustments of implements for mechanical weed control in a given crop. This 'conventional' approach neglects the systemic ('holistic') nature of organic agriculture, which has long been recognized as a pillar for the design of real, effective organic crop production systems (Andrews *et al.*, 1990; Lockeretz, 2000). In this respect, a too narrow view of weed management is questionable,

because of the likely underestimation of interaction effects among system components and of their carry-over across growing seasons, and may also result in information of little practical value to farmers.

The aim of this paper is to outline the reasons for and the potential benefits of tackling weed management in organic farming from a system perspective. After a reasoned analysis of the literature on this subject published recently, this paper illustrates how some peculiar features of organic systems suggest the need to undertake an integrated approach to weed management. Cover crop use is then presented as an important link between soil, crop, pest and weed management in organic systems. Two examples taken from recently published literature are reported to show the benefits of a system approach to weed management, i.e. the arrangement of a cropping system including an array of preventive, cultural and direct weed control methods. Lastly, future problems and perspectives of weed management in organic agriculture are outlined.

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The present framework

An analysis of the scientific literature published in major international sources in the period 1995–2000 has been carried out to reveal current research trends on issues related to weed management in organic agriculture. This analysis was based upon the outcome of several *Current Contents* (ISI, 2001) Boolean searches made by selecting: (1) 'organic' and 'weed'; (2) 'allelopathy' and 'weed'; (3) 'amendment' and 'weed'; (4) 'cover crop' and 'weed'; (5) 'cultivar' and 'weed'; (6) 'mulch' and 'weed', and (7) 'non-chemical' and 'weed' as keywords.

After clearance of the overlaps among search outcomes and of the occurrences clearly unrelated to organic farming, records were divided into 'reductionist' (i.e. those dealing with specific research issues out of a system framework), 'holistic' (i.e. those dealing with weed management in a system context) and 'other' (i.e. reviews and papers not clearly attributable to either of the previous groups). To have a clearer picture of the state of the art, occurrences included in each category

were then classified by subject and crop. In both cases, the number of occurrences was higher than the actual number of papers because several papers dealt with multiple subjects and/or crops. Papers with subjects not specifically aimed at organic systems but suggesting potential applications were retained; for example, this was the case with some of the papers dealing with allelopathy, biological weed control, and cover crops and mulches.

A total of 115 papers dealing with weed management in organic agriculture was published in the period 1995–2000 (average 19.2 papers year⁻¹). This is quite a low figure, although the trend in the average number of papers published per year is increasing (data not shown). Only about one-third of these papers were clearly 'holistic', whereas 57% were 'reductionist', and 12% were classified as 'other' (Table 1). Cover crops and mulches were the most studied subjects (19% of occurrences), followed by comparison between organic and conventional and/or integrated systems (12%) and allelopathy (8%). However, although the second issue

Table 1 Number of occurrences, divided by subject and typology*, retrieved by a literature search on weed management in organic agriculture (1995–2000)

Subject	Typology of occurrence			Total
	'Reductionist'	'Holistic'	Other†	
Allelopathy	14	1	2	17
Biodiversity	0	3	1	4
Biological weed control	3	0	0	3
Chemical vs. non-chemical weed control	8	2	0	10
Conventional vs. low-input vs. organic systems	2	23	0	25
Conversion to organic cropping/farming systems	0	2	0	2
Cover crops and mulches	30	4	4	38
Crop genotype	6	0	2	8
Crop rotation	0	4	3	7
Crop sowing (date, rate, pattern)	2	0	1	3
Crop:weed competition	4	0	3	7
Economics of weed management	0	2	0	2
Energy efficiency of weed management	0	1	0	1
Intercropping	1	1	4	6
Mechanical weed control	6	0	3	9
Soil amendments and fertilisers	7	4	1	12
Soil quality	1	5	0	6
Soil solarization	1	0	1	2
Thermal weed control (e.g. flame weeding)	2	0	1	3
Tillage system	5	0	0	5
Weed population dynamics	3	4	0	7
Weed seedbanks and weed seed germination	3	1	0	4
Weed survey	0	10	0	10
Weeds:insects interactions	1	3	0	4
Weeds:pests:diseases interactions	0	2	1	3
Others	1	1	1	3
Total papers	65	36	14	115
Total occurrences	100	73	28	201

*Based on the *Current Contents* database (ISI, 2001). Details on the search criteria used are reported in the text.

†Reviews and occurrences not clearly attributable to either 'reductionist' or 'holistic' categories.

was obviously mainly approached from a 'holistic' perspective (92% of occurrences), both cover crops/mulches and allelopathy were mostly approached from a 'reductionist' perspective (79% and 82% of occurrences respectively), as well as other important subjects such as soil amendment and fertilization (58%), soil tillage (100%) and mechanical weed control (67%). Ten occurrences (5% of total) dealt with weed surveys conducted in organic cropping and farming systems.

Classification of papers according to crop is shown in Table 2. Nearly half the papers (49%) involved studies on field crops, mainly winter cereals (21% of total), grain maize and sorghum (13%), and rice (8%). About one-third of the papers (34%) dealt with vegetable crops, whereas studies on tree crops/shrubs and fodder crops represented 12% and 4% of the total respectively. In all but the last category, most of the studies were conducted in a reductionist context (> 60% in the case of vegetable crops and tree crops/shrubs).

The results of this literature search show that researchers often tend to separate weed management and control from the overall context of organic systems management. The risk of this approach is that several important interactions among system components may be downplayed (if not neglected) or misunderstood, thus rendering the research outcome of little practical value.

The necessity of studying crop:weed interactions in a long-term system perspective

There is nowadays an increasing consensus on the idea that a thorough understanding of complex biological systems such as agro-ecosystems requires a system ('holistic') approach (Conway, 1987; Ikerd, 1993). Agro-ecosystems are complex entities made up of several components interacting with one another across space and time in such a way that their specific effects

Table 2 Number of papers, divided by cash crop and typology*, retrieved by a literature search on weed management in organic agriculture (1995–2000)

Cash crop	Typology of paper		
	'Reductionist'	'Holistic'	Total
Grain maize and sorghum	5	8	13
Oilseed rape	0	1	1
Peanut	1	0	1
Rice	8	0	8
Soyabean	0	1	1
Sugar beet	2	1	3
Winter cereals (barley, oats, rye, wheat)	11	10	21
Winter rape	0	1	1
<i>Field crops (total)</i>	<i>27</i>	<i>22</i>	<i>49</i>
Bell pepper	3	0	3
Beans (<i>Phaseolus</i> spp.)	2	3	5
<i>Brassica</i> spp.	3	1	4
Carrot	2	0	2
Faba bean	1	0	1
Leek	1	0	1
Onion	4	0	4
Peas (<i>Pisum</i> spp.)	1	1	2
Potato	2	2	4
Strawberry	0	2	2
Tomato	2	4	6
<i>Vegetable crops (total)</i>	<i>21</i>	<i>13</i>	<i>34</i>
Agroforestry systems	1	0	1
Coffee	1	0	1
Hop	0	1	1
Orchards	4	3	7
Tree nurseries	2	0	2
<i>Tree crops/shrubs (total)</i>	<i>8</i>	<i>4</i>	<i>12</i>
<i>Fodder crops (leys and pastures)</i>	<i>1</i>	<i>3</i>	<i>4</i>
Total papers	57	42	99
Total occurrences	113	81	194

*Based on the *Current Contents* (ISI, 2001) database. Details on the search criteria used are reported in the text.

cannot easily be separated from the system itself. As a consequence, agro-ecosystems are recognized as independent dynamic entities possessing a behaviour of their own (Oberle & Keeney, 1991; Pearson & Ison, 1997).

Compared with conventional systems, organic agro-ecosystems have some peculiar features that enforce the need to study their components (including weeds and their management) in a global framework, i.e. by taking into account any possible interactions with the other system components occurring across space and time. In organic cropping systems, the effects of cultural practices on crop:weed interactions typically manifest themselves more slowly compared with conventional systems, both in the short (during a crop cycle) and in the long term (during one or more crop rotation cycles). Consequently, crop and weed management in organic agriculture should be tackled in an extended time domain and needs to be deeply integrated. Examples on crop fertilization and direct weed control are reported hereafter to explain why this is necessary.

Crop fertilization

Crop:weed interactions and weed community dynamics can be greatly influenced by crop fertilization strategy. Organic systems rely upon the use of organic fertilizers and amendments that typically release nutrients (especially N) at a slower rate compared with mineral fertilizers (Magdoff, 1995). Nutrient release rate is largely dependent upon the C:N ratio of the source, soil properties, climatic conditions and incorporation method, which together determine the mineralization rate of the organic matter incorporated in the soil (Bouldin *et al.*, 1984; King, 1984; Maynard, 1993).

Faster nutrient release is often advantageous to weeds, which are usually able to take up nutrients in earlier growth stages more quickly and efficiently than crops (Jørnsgård *et al.*, 1996; Liebman & Davis, 2000), although this effect seems to turn into a competitive advantage only when initial weed stand density is high (Di Tomaso, 1995). Although slower nutrient release from organic sources should not result in increased weed competitive ability (Paul & Beauchamp, 1993; Liebman & Davis, 2000), it may favour the occurrence of late-season weed emergence flushes that contribute to seedbank replenishment and consequently to higher weed seedling recruitment in subsequent years. For example, such an effect has been observed in the nitrophile species *Stellaria media* L. (Bastiaans & Drenth, 1999). However, McCloskey *et al.* (1996) observed a decline in a *S. media* population over 3 years of application of poultry manure. The same authors also observed a negative effect of repeated organic fertiliza-

tion on *Sinapis arvensis* L., whereas *Galium aparine* L. population density increased. In contrast, Stevenson *et al.* (1998) did not find any significant effects of fertilizer type on barley weed populations. Inconsistency of effects, sometimes also observed for the same species, suggests that broad generalizations on the effect of organic fertilizers on weed population dynamics should be avoided, as they may vary upon: (1) source of organic matter; (2) pedo-climatic conditions; and (3) relative species abundance in the weed community.

Additionally, organic amendments and fertilizers may represent a source of incoming viable weed seeds, e.g. when farmyard manure, composts or slurry have not been treated enough before their application to soil (Sances & Ingham, 1997). Mt Pleasant & Schlater (1994) observed that 1 kg of cattle manure contained up to 42 viable *Chenopodium album* L. seeds, and Zimdahl (1993) reported that, in the same weed species, about 20% of the seeds ingested by cattle were able to withstand passage in the rumen and subsequent manure preparation and storage. The use of composts may alleviate this problem, because temperatures reached during the composting phase are usually high enough to kill most weed seeds (De Luca & De Luca, 1997). Complete loss of seed viability has been observed in several weed species after windrow composting of feedlot manure for 4 weeks (Tompkins *et al.*, 1998) or of municipal wastes for > 3 d (Grundy *et al.*, 1998), with temperatures ranging from 55 to 65 °C. To achieve a significant reduction in seed viability, a base temperature above 46 °C seems to be required (Nishida *et al.*, 1998), whereas the duration of composting appears to be less important (Ozores-Hampton *et al.*, 1999). Also, storage of slurry in lagoons for a minimum period of 3 months can significantly reduce weed seed viability (Sartorato *et al.*, 2001), and application of composted manure can substantially reduce weed emergence, especially of small-seeded species, because of physical and chemical (via the production of leachates) effects (Ligneau & Watt, 1995). These leachates can also be produced in the windrow when the compost is kept constantly moist (Eghball & Lesoing, 2000). It is worth mentioning that manure can also be used as a cheap substrate for the field introduction of fungi (e.g. *Trichoderma* spp.) used for biological weed control (Hutchinson, 1999).

Crop:weed competition and weed community dynamics may also be altered by fertilization management. Appropriate timing of N mineral fertilization has been proposed in integrated cropping systems as a mean to unbalance nutrient competition between crop and weeds to the benefit of the former. In practice, this approach implies prior knowledge of the weed flora that is likely to develop in a field: top-dressing N fertilization can conveniently be anticipated or delayed when late- or

early-emerging species prevail respectively. Research on competition effects between sugar beet (*Beta vulgaris* L. var. *saccharata*) and *S. arvensis* (an early-emerging species) or *C. album* (a late-emerging species) demonstrated the feasibility of this approach (Paolini *et al.*, 1999). However, preliminary results of studies in which durum wheat (*Triticum durum* Desf.) competed with naturally occurring weed populations showed that this effect is not systematic but depends on seasonally variable climatic conditions, which in turn affect nutrient release in the soil and weed community composition (R Paolini & P Bärberi, unpubl. obs.). In organic systems, it is likely that this effect could be even less systematic, because the composition of organic fertilizers and amendments – especially of those produced on farm – typically varies between seasons, thereby representing an additional source of variation that influences nutrient release rates. Carry-over of nutrients from one growing cycle to the next should also be expected, especially when organic matter is applied in autumn or winter, when the mineralization rate of organic matter is low. As a consequence, the influence of organic fertilization on crop:weed relationships and weed population dynamics is probably present over a wider time period compared with mineral fertilization.

Variable composition of organic fertilizers and amendments makes it difficult to tailor a weed management strategy for organic farming using nutrient manipulation to improve crop competitive ability, although an exception might be represented by injection (side-dressing) of faster nutrient-releasing organic materials (e.g. slurry) at the sowing of row crops (Rasmussen, 2000).

The necessity of studying crop:weed interactions with a system approach also stems from the observation that nutrient management in organic farming is also intertwined with tillage system, as some organic amendments (e.g. manure) usually need to be ploughed down, whereas others (e.g. cover crops) can also be profitably managed with reduced tillage. Annual grasses, such as *Alopecurus myosuroides* Huds. (Cousens & Moss, 1990) and *Bromus sterilis* L. (Froud-Williams, 1983), can be expected to increase with shallow incorporation of organic material in soil, because of their reduced seed dormancy and capability of emerging from only shallow soil depth. Moreover, small-seeded (e.g. *Amaranthus* spp.) and wind-dispersed (e.g. *Sonchus* spp.) weeds may find better opportunities to establish in minimum-tilled soil than in ploughed soil (Zanin *et al.*, 1997; Bärberi *et al.*, 1998a). Similarly, reduced soil disturbance may favour biennial and perennial species, especially when organic matter is incorporated with PTO-powered rotary implements that cause fragmentation of vegetative propagules such as buds, rhizomes and tubers (Anderson, 1999). Perennial species such as *Cirsium*

spp. and *Elymus repens* L. have been cited as troublesome weeds in organic farming systems in northern Europe (Rasmussen *et al.*, 1999; Rydberg & Milberg, 2000). It should be remembered that the abundance of perennial weeds in these countries is also favoured by the widespread adoption of crop rotations in which the share of perennial leys (e.g. grass/clover), sometimes coupled with the use of catch crops, is quite high, usually above 50% (Olesen *et al.*, 2000). Lack of primary tillage during the ley and catch crop phases, coupled with elimination of annual weeds by repeated mowing (Bulson *et al.*, 1996), probably shifts weed community composition towards prevalence of vegetatively reproducing species.

Intensification of the studies on nutrient release dynamics and its relationship to crop management systems would help to clarify crop:weed interactions and weed community dynamics, two major steps necessary for the design of successful weed (and crop) management strategies in organic systems.

Direct weed control

Compared with herbicides, direct physical weed control (PWC) methods such as harrowing, hoeing or flaming are usually less effective, both in the short (within a growing cycle) and long term (across growing cycles).

Lower short-term effectiveness of PWC depends upon its reduced persistence of action and/or control. Whereas herbicides can persist in the soil for weeks (if not months in the case of residual herbicides), PWC may stimulate further weed emergence (in the case of mechanical weed control) or allow recovery from damage (in the case of both mechanical and thermal weed control, e.g. see Kurstjens & Bleeker, 2000).

Soil disturbance caused by working implements brings new weed seeds close to the soil surface and may enhance soil N mineralization (Becker & Böhrnsen, 1994) – both effects are conducive to subsequent weed emergence flushes. This effect, which is positive in the false seedbed technique as it helps to deplete the weed seedbank *before* crop sowing, is usually negative when it takes place *during* the crop cycle, especially when the crop is already too tall to allow any additional passes of the tool(s) used for mechanical weed control. Although recent technological advances such as torsion weeders (Ascard *et al.*, 1999; Kurstjens & Bleeker, 2000) or self-steering hoes have shown promising results in both arable and vegetable crops, intrarow mechanical weed control remains problematic, leading to reduced overall effectiveness of PWC. Also, some weed species (e.g. grasses and other monocots) have morphological traits (e.g. the protection of the vegetative apex by folded young leaves) that make them less sensitive to heat

damage (e.g. by flaming). Consequently, they may quickly recover from thermal stress, especially if they are large, thereby decreasing the overall treatment effectiveness (Ascard, 1994).

Limited effectiveness of PWC is also related to lower flexibility of non-chemical methods compared with chemical ones (at least, this holds for those crops for which herbicide choice is ample). Mechanical weed control is a viable option only within a certain range of soil conditions, the amplitude of which varies upon soil type and implement used (Bowman, 1997). For example, excessive soil moisture impedes field workability and may delay mechanical weed control until the crop is too high or weeds are too well developed. In the case of spring-tine harrowing, high soil moisture also increases the risk of crop damage (Peruzzi *et al.*, 1997).

Compared with herbicide use, higher risk of incomplete weed control and lower systematicity of outcome usually results in lower long-term effectiveness of PWC, also related to a progressive build-up of the weed seedbank resulting from seed production by surviving or late-emerging weeds (Bastiaans & Drenth, 1999). Out of a system context, it can then be expected that herbicides provide more effective and stable weed control than physical methods.

For this very reason, it is important not to rely on PWC as the only means of controlling weeds in organic systems, but to integrate it in an overall crop and weed management strategy arranged at the system scale. Integration of direct weed control with other cultural practices (crop and cultivar choice, tillage, fertilization, etc.) in a system context is the creed of integrated weed management systems (IWMS), which are recognized as the best approach to tackling weed problems anywhere (Swanton & Weise, 1991; Zimdahl, 1995). This approach is even more important in organic systems, where herbicide use is forbidden.

Building up a good weed management system

Improvement in the effectiveness of PWC passes through the adoption of a global approach to weed problems. In practice, this means that PWC must necessarily rely on prior application of agronomic practices aimed to: (1) reduce weed emergence through the use of preventive methods (crop sequence choice, primary tillage, false seedbed technique, use of cover and/or smother crops); and (2) reduce weed competition through cultural methods that improve crop competitive ability (use of appropriate crop genotypes, transplants, sowing/planting pattern, fertilization strategy). Agronomic practices may preferentially exert the first or second effect or both (Table 3). Thus, theoretically,

organic farmers have an ample arsenal of practices to include in an IWMS. Obviously, the choice of one practice instead of another depends upon pedo-climatic conditions, socio-economic constraints and farmers' risk perception (Gunsolus & Buhler, 1999).

Preventive methods

It is not new to say that the foundations of successful weed management lie in an appropriate cropping system design. Maximum diversification of the cropping system (i.e. of crops and associated cultural practices), e.g. alternation between winter and summer crops, grain and root crops, nutrient-depleting and nutrient-building crops, as well as the inclusion of a ley phase, disrupt the regeneration niches of different typologies of weeds (annuals, biennials, perennials, obligate seasonal species), thereby preventing the establishment of a specialized flora and promoting that of a multifaceted weed community hosting numerous species each present at a low density (Buhler, 1999). It follows that crop rotations (in the strict sense) should rather be replaced by crop sequences without any rigid preplanned scheme in order to lower as much as possible the risk of weed adaptation to a repeated cultural regime. In this context, even a 'perfect' crop rotation would need to be modified from time to time.

Diversification of the crop sequence brings about the diversification of primary tillage (e.g. alternation between ploughing and non-inversion tillage), as well as of type and timing of seedbed preparation techniques (false seedbed technique, ridging) and cultivation. Combination of all these factors, which by themselves represent additional means of reducing weed emergence during a crop growing cycle, contributes to the long-term success of weed management in organic systems (Welsh *et al.*, 1999).

Among preventive methods, the use of cover crops in organic systems merits a special mention because of their contribution to increased agro-ecosystem health (Lal *et al.*, 1991). Owing to their beneficial effects on soil conservation, soil nutrient cycles, pest, pathogen and weed populations, cover crops can represent an ideal bridge between soil, nutrient, pests and weed management in an organic system and, as such, optimization of their use may be crucial for the success of the system itself.

Cover crop effects on weeds largely depend upon cover crop species and management, following cash crop and weed community composition (Bärberi & Mazzoncini, 2001). Prevention of weed emergence is exerted partly through competition for light, nutrients and soil moisture during the cover crop growing cycle, and partly through physico-chemical effects occurring

Table 3 Classification of cultural practices potentially applicable in an integrated weed management system for organic farming, based on their prevailing effect (modified after Bärberi, 2000)

Cultural practice	Prevailing effect	Example	Main references
Crop rotation	Reduction in weed emergence	Alternation between winter and spring–summer crops	Karlen <i>et al.</i> (1994); Buhler (1999); Welsh <i>et al.</i> (1999)
Primary tillage	Reduction in weed emergence	Deep ploughing, alternation between ploughing and reduced tillage	Froud-Williams (1988); McCloskey <i>et al.</i> (1996); Bärberi <i>et al.</i> (2001)
Seedbed preparation	Reduction in weed emergence	False/stale-seedbed technique	Caldwell & Mohler (2001)
Cultivation	Reduction in weed emergence	Post-emergence harrowing or hoeing, ridging	Rasmussen (1992); Bowman (1997); Kurstjens <i>et al.</i> (2000)
Cover crops	Reduction in weed emergence	Cover crop grown in-between two cash crops and used as green manure or dead mulch	Blum <i>et al.</i> (1997); Liebman & Davis (2000); Teasdale & Mohler (2000); Bärberi & Mazzoncini (2001)
Intercropping	Reduction in weed emergence, improvement in crop competitive ability	Cover crop used as living mulch, intercropped cash crops	Ofori & Stern (1987); Liebman & Dyck (1993); Baumann <i>et al.</i> (2000)
Thermal weed control	Reduction in weed emergence	Pre-emergence or localized post-emergence flame-weeding	Ascard (1994, 1995)
Mulching/soil solarization	Reduction in weed emergence	Use of black or transparent films (in glasshouse or field)	Horowitz <i>et al.</i> (1983); Sauerborn <i>et al.</i> (1989)
Crop genotype	Improvement in crop competitive ability	Use of cultivars characterized by quick emergence, high growth and soil cover rates in early stages	Lemerle <i>et al.</i> (1996, 2001); Rasmussen & Rasmussen (2000); Olofsdotter (2001)
Sowing/planting	Improvement in crop competitive ability	Use of transplants, higher seeding rate; lower inter-row distance; anticipation of, or delay in sowing/transplant date	Mohler (1996); Spandl <i>et al.</i> (1998); Melander (2000)
Fertilization	Reduction in weed emergence, improvement in crop competitive ability	Use of slow nutrient-releasing organic fertilizers and amendments; fertilizer placement	Paolini <i>et al.</i> (1999); Liebman & Davis (2000); Rasmussen (2000)
Irrigation	Reduction in weed emergence, improvement in crop competitive ability	Irrigation placement (micro/trickle-irrigation)	Berkowitz (1988)

when cover crop residues are left on the soil surface or ploughed down (Mohler & Teasdale, 1993; Teasdale & Mohler, 1993). For example, interference with weeds, including competition, physical and allelopathic effects, is usually higher when species of the Gramineae and Cruciferae families are sown than with legume cover crops (Bodyston & Hang, 1995; Blum *et al.*, 1997), both *in vivo* and after cover crop destruction. Interference from cover crops and their residues is related to their capacity to occupy ecological niches otherwise available for weed development. This is mostly caused by the sequestration (into organic matter) of soil nutrients (especially N), the release of allelochemicals and modifications in the soil microenvironment (Gallandt *et al.*, 1999). For example, rye (*Secale cereale* L.) has been shown to possess both great N uptake capacity (Ditsch *et al.*, 1993) and the potential for releasing allelopathic compounds (Putnam, 1988; Yenish *et al.*, 1995).

Sorghum (*Sorghum* spp.) contains sorgoleone, a compound that has been proved to reduce weed emergence (Duke *et al.*, 2000). Glucosinolates contained in living and dead tissues of kale (*Brassica* spp.), rocket (*Eruca* spp.) and mustard (*Sinapis* spp.) also have high allelopathic potential (Jimenez-Osornio & Gleissman, 1987; Angelini *et al.*, 1998). In contrast, the weed-suppressive ability of annual legumes such as crimson clover (*Trifolium incarnatum* L.) and subterranean clover (*Trifolium subterraneum* L.) is usually lower; this has been attributed to the stimulatory effect on weed emergence of N released from cover crop residues, especially when they are ploughed down (Blum *et al.*, 1997). However, Teasdale & Mohler (2000) claimed that, when cover crop residues are left to decompose on the soil surface, weed suppression results mostly from physical effects of the mulch rather than nutrient or allelochemical effects. In an attempt to model weed

emergence as influenced by mulch physical properties, they showed that weed suppression was directly related to the mulch area index (mulch area divided by soil unit area), a parameter that varies considerably with the mulching material and greatly influences light extinction through the mulch (and consequently weed seed germination). The effect on the emergence of selected weed species was not uniform over a range of mulch masses: for example, the emergence of *A. retroflexus* was stimulated at low mulch masses ($< 400 \text{ g m}^{-2}$) and subsequently reduced. Weed species sensitivity to mulch physical effects seems to be inversely related to seed mass, an effect also observed for sensitivity to allelochemicals (Liebman & Davis, 2000).

In practice, the inclusion of cover crops in weed management strategies tailored to organic systems relies upon a better understanding of the interaction effects among cover crops features (species, cultivar, growth pattern) and their management (timing and method of killing and incorporation in soil, position in the cropping sequence) in different soil, climate and weed flora conditions.

In this respect, the importance of studying the interactions between weeds and other biota should also be stressed. For example, cover crops may influence insect population dynamics, e.g. providing a suitable habitat for the survival and reproduction of beneficial arthropods or – just like weeds – an alternative food source for arthropod pests (Norris & Kogan, 2000). Also, cover crops may promote the establishment of specific soil biota, e.g. vesicular–arbuscular mycorrhizae, which, in turn, may drive weed population dynamics by favouring mycorrhizal plant species to the detriment of non-mycorrhizal species (Jordan *et al.*, 2000).

Cultural methods

In this context, cultural weed management is referred to as the use of any methods that *directly* enhance crop competitive ability against weeds, i.e. methods applied during a crop growing cycle.

In this category, a first method is the use of crop genotypes that possess traits conferring a higher competitive ability against weeds. Usually, these traits are related to faster seedling emergence and canopy establishment (Rasmussen & Rasmussen, 2000) and higher growth rates in early stages. In Australia, a genotype screening conducted on wheat showed that it is possible to select cultivars that possess competitive traits against weeds (e.g. *Lolium rigidum* Gaud.) while maintaining an adequate grain yield potential (Lemerle *et al.*, 1996, 2001), although in most of them, the expression of competitive advantage is strongly influenced by environmental conditions (Lemerle *et al.*, 2001). Here, it should be pointed out that not all traits that give crops a competitive advantage against weeds may usefully be exploited in cropping systems; for example, plant height, which is usually correlated with weed suppression (Benvenuti & Macchia, 2000), is often negatively correlated with crop productivity and can also increase crop sensitivity to lodging, which may lead to severe yield losses. Higher crop competitive ability can also arise from the release of allelochemicals that inhibit weed emergence and growth. A study conducted on rice (Olofsdotter, 2001) showed that some cultivars are able to exert considerable allelopathic activity against weeds. Although the ranking of cultivars based on their allelopathic effect differed between field and laboratory trials (Table 4), there is potential for using genotype

Table 4 Weed suppressive ability of rice (*Oryza sativa* L.) cultivars under field conditions (dry seasons) compared with allelopathy screening under laboratory conditions (modified after Olofsdotter, 2001)

Cultivar	Field experiments				Laboratory screening		
	Weed biomass 1995 (g m^{-2})	Weed biomass 1996 (g m^{-2})	Weed tillers in row 1996 (no. m^{-1})	Biomass per weed (g per plant)	<i>Echinochloa crus-galli</i> root length (mm)	SE	Rank of whole data set
Lubang Red	148	188	45	5.4	35.8	2.4	1
YH1	151	230	50	5.8	37.1	2.4	3
Musashikogane	120	166	30	4.8	38.4	2.4	4
Taichung Native 1	129	274	64	5.3	42.6	2.4	5
Kouketsumuchi	144	106	33	2.9	42.8	2.4	6
Takanenishiki	141	126	29	3.9	46.6	2.4	14
AC 1423	116	219	42	7.2	46.8	0.9	15
Tan Gang	134	91	30	2.6	47.0	2.6	17
IR38 (control)	225	301	76	8.2	63.8	2.4	54
No-rice control	289	460	122	12.6	97.0	0.8	111
Mean of all cvs	187	281	57	7.6	58.9	–	–
SE	26	49	10	1.5	–	–	–
CV	28	35	35	40.0	26.0	–	–

choice as a cultural tool in rice weed management strategies. So far, selection of weed-suppressive genotypes has mainly been considered as a way of reducing herbicide rates in integrated cropping systems; however, it is clear that this approach may be even more important for organic systems.

In any case, cultural methods are effective if they are able to maximize the differential of development between crop and weeds to the advantage of the former (Mohler, 1996). In this respect, an additional tool available to the farmer is the use of crop transplants instead of seeds, which is particularly important in vegetable crops that are often poor competitors against weeds. Besides the enhancement of crop competitive ability, use of transplants has been proposed in sugar beet as a mean to increase selectivity (i.e. the ratio between damage to weeds and crop) of intrarow weed control by torsion weeders (Melander, 2000). In this case, mechanical weed control can already be performed 5 d after transplanting, with little damage to the crop. However, a negative side-effect of transplant use in sugar beet is excessive root forking, although this may be overcome by optimizing the seedling raising technique.

In some cases, modification of crop sowing date, density and pattern may also reduce weed emergence and/or increase crop competitive ability (Mohler, 1996; Griepentrog *et al.*, 2000). However, this effect cannot be generalized, as it is very much dependent upon crop species and location. For example, Spandl *et al.* (1998) observed that, compared with the autumn-sown crop, control of *Setaria viridis* (L.) Beauv. in spring-sown wheat increased because the weed tended to emerge in a single flush rather than in several flushes, thus becoming more sensitive to direct weed control methods. Obviously, in this case, the crop sowing date can be used as a weed management tool only in those environments where the farmer can actually choose whether to sow wheat in autumn or in spring and not, for example, in Mediterranean-type environments, where wheat can only be sown in autumn. In vining pea (*Pisum sativum* L.), an increase in the seeding rate may turn into a higher competitive ability, but often to the detriment of grain yield because of the concurrently higher intraspecific competition (Lawson & Topham, 1985). Similarly, in potato (*Solanum tuberosum* L.), a higher planting density may turn into a crop competitive advantage but may also decrease tuber quality and increase crop susceptibility to diseases (Litterick *et al.*, 1999). In contrast, in crops showing higher phenotypic plasticity, modification of seeding rates and/or pattern may have a better chance of being exploited in weed management strategies. For example, this is probably the case in pigeon bean (*Vicia faba* L. var. *minor* Peterm. Em. Hartz), a grain legume that is gaining interest in

Mediterranean organic cropping systems as a protein source for animal feed and a soil fertility-building crop. Pigeon bean can be sown either in narrowly spaced rows (c. 15 cm) or in widely spaced rows (up to 70 cm). In the first case, pod number and grain yield per plant decrease markedly and height of pod insertion on the stem increases, which reduces yield losses resulting from mechanical harvest. In both cases, grain yield per unit area and seed crude protein content are equally good (Bonari & Macchia, 1975). Thanks to its phenotypic plasticity, it is likely that the seeding pattern (and consequently crop productivity) in organic pigeon bean may be optimized further, e.g. by sowing the crop in paired rows and using an inter-row distance (c. 40–50 cm) that allows hoeing between the rows.

Another tool available to the organic farmer for increasing crop competitive ability against weeds is intercropping. Just like cover crops, intercrops increase the ecological diversity of farms and, by increasing the use of natural resources by the canopy compared with monocrops, often deprive weeds of the light, water and nutrients necessary for their development (Liebman & Dyck, 1993). Use of intercropping may be seen more favourably by organic farmers than the use of cover crops (as living mulches) because, in the first case, all the component species are cash crops. Recently, Baumann *et al.* (2000) showed that, compared with sole crops, a leek:celery intercrop sown in a row-by-row replacement design decreased relative soil cover of weeds by 41% and, in another experiment, reduced the density and biomass of *Senecio vulgaris* L. by 58% and 98%, respectively, mostly thanks to decreased light transmission through the canopy. Additionally, the intercrop gave a 10% yield increase compared with the sum of the yields given by sole crops. Weed suppression and crop yield increased in cereal:legume intercrops such as winter wheat:fabia bean (*Vicia faba* L.) (Haymes & Lee, 1999), winter wheat:pea (Paolini *et al.*, 1993) and wheat:field beans (*Phaseolus vulgaris* L.) (Bulson *et al.*, 1990). It is well known that, as in the case of living mulches, the success of intercropping relies upon fulfilling at best the requirements of the component species for natural resources (e.g. light interception and soil layers explored by crop root systems) in order to increase resource use complementarity and decrease interspecific competition. In practice, this means optimizing species spatial arrangement, their relative plant densities and their relative growth over time (Ofori & Stern, 1987).

Direct weed control methods

The present boom in organic farming in industrialized countries has renewed the interest of agricultural

machinery companies in the development of innovative tools for physical (especially mechanical and thermal) weed control. A review of the most notable technical innovations recently developed for direct weed control is beyond the scope of this paper. Technical issues related to mechanical and weed control are exhaustively treated by Bowman (1997), while in-depth discussion of issues related to thermal weed control can be found in Ascard (1995).

Most of the technical innovations developed recently in physical weed control are related to new equipment available for intrarow weed control in arable and vegetable crops. Among these, it is worth mentioning brush weeders (Melander, 1997; Fogelberg, 1998; Fogelberg & Dock Gustavsson, 1999), finger weeders (Ascard & Bellinder, 1996) and torsion weeders (Kurstjens & Bleeker, 2000; Melander, 2000). Recent studies have shown that, in spring-tine harrowing (Kurstjens *et al.*, 2000; Kurstjens & Kropff, 2001), torsion weeding (Kurstjens & Bleeker, 2000) and brush weeding (Fogelberg & Dock Gustavsson, 1999), weed control is mostly dependent upon the uprooting of seedlings rather than their burial with soil. Generally, the effectiveness of mechanical weed control is very much influenced by soil type and conditions (especially soil moisture content), weed species composition and relative growth stage of crop and weeds (Rasmussen, 1992; Wilson *et al.*, 1993; Rasmussen & Ascard, 1995). Information on the suitability of each implement for different crops and pedo-climatic conditions is still incomplete, although it is by far the most widespread type of research conducted on mechanical weed control (see Table 1). However, just because of this dependency on site-specific conditions, research aimed only at finding the optimum technical adjustment of machinery for mechanical or thermal weed control may not always be of practical value to organic farmers. For example, it has been shown that soil, crop and weed conditions consequent to the use of ploughing or no tillage influenced the effectiveness of spring-tine harrowing in durum wheat to a much greater extent than any adjustments in tine angle (Bärberi *et al.*, 2000). For organic farming research, it is therefore strongly advisable to follow an approach aimed first at optimizing the system and only afterwards, within that system, to optimize specific cultural practices such as mechanical weed control.

High-tech solutions for physical weed control, such as 'electroporation' (i.e. the application of electric pulses to soil; Fogelberg, 2000), CO₂ lasers (Heisel *et al.*, 2001), precision guidance systems (Chamen, 2000) or crop and weed optical detection methods (Bontsema *et al.*, 2000; Kielhorn *et al.*, 2000), have already been developed. However, the enormous costs of some of this equipment make their widespread use very unlikely in

real farm conditions, even for high-value cash crops. To date, the most urgent issues to be tackled in organic systems, at least in developed countries, are (1) to reduce the time needed for hand-weeding, which is sometimes up to 400 h ha⁻¹ or more (Vereijken *et al.*, 1998; cited by Kropff *et al.*, 2000; van der Weide & Bleeker, 2000); and (2) to make implements for direct weed control available to farmers at a reasonable price (Kropff *et al.*, 2000).

Towards 'holistic' weed management

For the reasons outlined previously, fine-tuning of weed management strategies in organic agriculture must rely upon increased knowledge of (1) weed (and crop) ecology in a given agro-ecosystem, and (2) cropping system influence on weed population dynamics. Both types of information would allow a better understanding of those factors driving crop:weed interactions in specific organic farming systems. It is then germane that crop and weed management needs to be integrated, making full use of agro-ecological knowledge (Buhler, 1999). As a consequence, the concept of weed management *per se* becomes fuzzy, as it is not possible to disentangle it from cropping system management, in contrast to what usually happens in conventional agriculture. This system approach, although certainly perceived as important by weed scientists, is very rarely encountered in research papers. There are, however, a few notable exceptions, two of which are reported here to illustrate that weed management in organic agriculture can be successful when tackled in a global ('holistic') context. In these examples, the physical boundary of the system (and hence the term 'holistic') is referred to the field (case study 1) or the farm (case study 2).

Case study 1: winter cereal:row crop 2-year rotation

The first example is taken from Melander & Rasmussen (2000) and refers to a 2-year rotation between a winter cereal and a row crop (sugar beet or a vegetable crop). This system has been developed for either integrated or organic cropping systems including a poorly competitive crop (the row crop). The aim of this weed management system is to stimulate weed emergence as much as possible (i.e. to deplete the weed seedbank) during the year in which the highly competitive crop (the cereal) is grown so that, in the following year, fewer weeds will emerge within the row in the poorly competitive crop. Winter wheat or barley is grown in the first year, leaving 25-cm-wide unsown bands in between the cereal rows (Fig. 1). These bands are repeatedly hoed to stimulate the emergence of weed seedlings, which are destroyed by the following pass. In the next year, either sugar beet or a vegetable crop (e.g. kale, *Brassica oleracea* L. var.

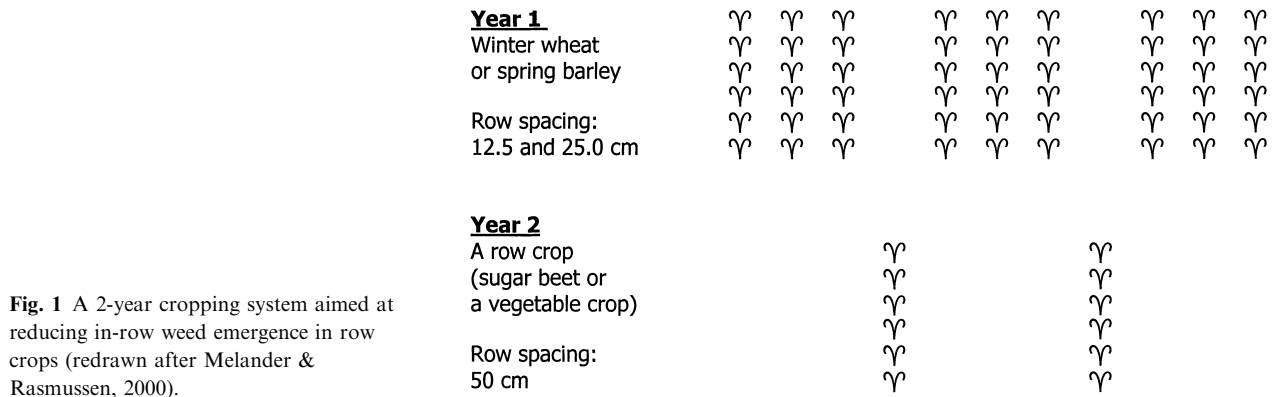


Fig. 1 A 2-year cropping system aimed at reducing in-row weed emergence in row crops (redrawn after Melander & Rasmussen, 2000).

acephala DC. subvar. *laciniata* L., or onion, *Allium cepa* L.) is drilled directly on these bands. Lack of soil ploughing in the second year avoids bringing new weed seeds up to the soil surface, an effect that would otherwise counteract the benefits of previous weed seedbank depletion.

With spring barley, the authors achieved an 81–92% reduction in weed emergence compared with the previous year and a further 62–73% reduction in the case of prevention of seed shedding. However, with winter wheat, no appreciable weed emergence reduction was observed, probably because of a less susceptible weed flora compared with that emerging in spring-sown crops (barley or vegetable crops). Obviously, reduced in-row weed emergence in the second year cuts down the costs related to hand-weeding.

Although this management system is not completely 'holistic' (e.g., it does not involve nutrient management), it is clear that its strength is to frame the weed management strategy at the cropping system level by taking into account the interactions between crop sequence, soil tillage and weed management. The authors pointed out that this system needs to be improved in terms of: (1) the reduction in seed shedding in the unsown bands, especially from species with highly mobile seeds (e.g. *Cirsium* spp., *Sonchus* spp. and

Taraxacum officinale Weber); and (2) the control of perennial weeds, which may take advantage of the lack of primary tillage in the second year.

Case study 2: weed management system for organic onion production

This second example has been taken from a paper by Nordell & Nordell (1998) and is based on the work of two Pennsylvanian vegetable growers (the authors themselves).

Onion is a crop characterized by slow emergence and early growth which provides little soil cover and, as such, is highly sensitive to competition from weeds. It follows that weed management, especially in organic production, is usually perceived as highly problematic. Based on their practical experience, the authors have developed a cropping system in which several cultural practices are laid down in the 2-year period between the harvest of the previous vegetable crop and onion sowing, with the specific purpose of reducing weed emergence during the onion growing cycle (Fig. 2).

In the autumn after harvest of the preceding crop, a cereal cover crop (oats or rye) is sown and mowed repeatedly until it is ploughed down in the next spring. Mowing aims to impede seed shedding from annual

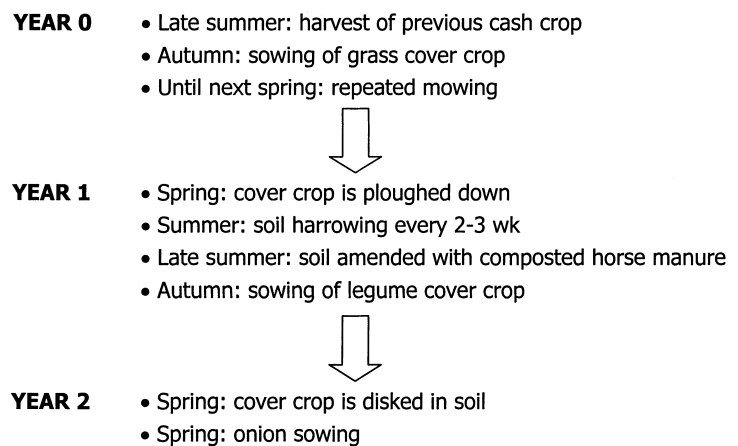


Fig. 2 Schematic representation of a 2-year whole-farm weed management system aimed at reducing weed emergence in organically grown onions (after Nordell & Nordell, 1998).

weeds and to promote regrowth of the cereal, in order to achieve a consistent mulch effect over the season that inhibits weed development further. During the next summer, the soil is harrowed every 2–3 weeks to deplete the seedbank and bring propagules of perennial weeds up to the soil surface, where they are killed by heat and drought. In the late summer, composted horse manure produced on farm is incorporated in the soil. The authors claim that the use of this amendment, compared with fresh manure or fast nutrient-releasing organic fertilizers, is less stimulatory to weed emergence. In the early autumn of the second year, a legume cover crop (e.g. pea) is sown. This cover crop, besides enhancing soil fertility, further reduces annual weed growth over the following winter season. Lastly, this second cover crop is incorporated in the soil with a disc harrow just before onion transplanting. According to the authors, both weed incidence and hours needed for hand-weeding can be substantially reduced already after two or three cycles of this cropping system. The land surface yearly subtracted from cash crop growing using this system can be reduced by readjusting the crop rotation to limit the share of farm arable land actually cropped with onions in a given year.

Although this system is obviously not directly transferable to different agricultural environments, its approach could serve as a reference for developing similar cropping and farming systems elsewhere, based on the use of on-farm produced manure, locally adapted cover crop species and mechanical interventions optimized (in terms of type, frequency and timing) according to local crops and weed species abundance. This example shows that, where their use is not constrained by climatic factors, cover crops may represent an excellent link between soil, crop and weed management (another example of this kind can be found in Bärberi *et al.*, 1998b) and, as such, their inclusion in organic cropping systems should always be recommended.

Future perspectives

Many organic farmers are aware, at least instinctively, that successful weed management implies putting into practice the concept of maximum diversification of their cropping system, and on-farm experiences like the one just shown help to pinpoint this feeling. However, this task is often difficult to achieve, because practical solutions have to pass through local filters, such as soil and climate conditions, availability of and accessibility to external inputs (seeds, crop cultivars, machinery, etc.) and socio-economic constraints (market, tenure status, attitude towards entrepreneurial risk, etc.). From an agronomic viewpoint, it is possible to foresee a few issues having direct and indirect implications for weed

management that may become important in the near future because of oncoming legislative constraints or their promising – yet only partially explored – perspectives for practical application. Three of these issues are taken as examples and discussed briefly here.

Quality of organic seeds

From 31 December 2003, in the European Union it will be compulsory to use organically produced seeds for sowing organic crops. At the moment, however, the demand for organic seed is much higher than its availability (Cook & Wolfe, 2000). It can easily be predicted that weed control will be one of the main technical problems to be solved in organic seed crops. To avoid severe competition from weeds, these crops would require direct (mechanical or thermal) weed control to be often supplemented by hand-weeding, both at an early stage (to prevent negative effects on seed filling and, consequently, on germinability) and before harvest (to avoid weed seed shedding and consequent decrease in crop seed purity and increase in seed cleaning costs). It follows that the cost of organic seeds may become prohibitive, especially in the case of poorly competitive vegetable crops that would probably require more labour for hand-weeding. Besides this, low-quality, scarcely pure seeds might get to the market at a much lower cost and, as such, become attractive to farmers. These seeds would represent a source of weed infestation, leading to increased weed management problems for many subsequent years. In this perspective, while scientists are required to refine technical solutions aimed at reducing the costs of direct weed control (especially those related to hand-weeding), all the other actors involved in organic agricultural production (policy-makers, organic farming certification bodies, extension services and farmers themselves) will have to take action to ensure easy access to good quality seeds at a reasonable price.

Increasing biodiversity in agro-ecosystems

It has long been recognized that, in agro-ecosystems, an increase in biodiversity at any level (crops, weeds, arthropods, soil microbes, etc.) usually results in better and more stable agro-ecosystem health and productivity (Andow, 1991; Altieri, 1995). Typically, organic farming promotes higher biodiversity compared with conventional farming (Soil Association, 2000; Stolton *et al.*, 2000).

The use of cover crops and organic amendments, via the promotion of diversity in insect, fungal, bacterial or mycorrhizal communities, may alter antagonist or competitive effects to the benefit of crops and to the

detriment of weeds (Jordan *et al.*, 2000; Liebman & Davis, 2000; Norris & Kogan, 2000). Once factors driving these effects are better understood, it might be possible to use this knowledge to improve organic weed management systems locally.

It would also be helpful to find indicators of 'functional' biodiversity, where weed species abundance is weighted on the role that they have in the agro-ecosystem (e.g. strong/weak competitors, promoters of the presence of beneficial arthropods, etc.). For example, highly competitive species could be assigned a different weighting than poorly competitive species, so that the overall diversity value (at the weed community level) might reflect these differences and consequently be evaluated from a more practical (i.e. farmer-wise) perspective.

Allelopathy

Management of allelopathy, defined here as 'any process that involves secondary metabolites produced by plants, algae, bacteria, and fungi that influence the growth and development of biological systems' (IAS, 1996), is another potential tool in the arsenal of the organic farmer. As mentioned before, several crops (some of which can be used as cover crops) have been proved to release allelopathic compounds in the soil (Inderjit & Keating, 1999), many of which have been chemically characterized (Inderjit, 1996; Seigler, 1996; Waller *et al.*, 1999). The idea of exploiting these compounds as 'natural herbicides' is therefore very appealing (Putnam, 1988; Weston, 1996; Duke *et al.*, 2000). However, the large majority of the studies carried out on this topic have referred to 'reductionist' trials carried out in controlled environments (see Table 1), often with the only aim to extract and characterize allelochemicals or, at the most, to test the effect of these compounds on the germination of selected sensitive species in bioassays. In the case of crop:weed interactions, absolute evidence of the occurrence of allelopathy in the field is difficult to obtain, mainly because allelopathic effects are difficult to disentangle from resource competition and other biotic effects (Qasem & Hill, 1989; Weidenhamer, 1996; Inderjit & del Moral, 1997). Additionally, the production and release of allelochemicals depend largely upon environmental conditions, usually being higher when plants are under stress, e.g. extreme temperatures, drought, soil nutrient deficiency, high pest incidence (Einhellig, 1987); also, the range and concentration of chemicals that a given species can produce can vary accordingly (Anaya, 1999). Other effects that need to be examined are allelopathy-mediated weed:weed, weed:crop and crop:following (or companion) crop interactions. It is

therefore questionable whether allelopathy management *per se* would ever represent a consistently effective weed management tool; however, a better understanding of allelopathic occurrence in field situations, and of how it is influenced by cultural practices, would make it possible to include allelopathic crops in organic cropping systems and use them as a complementary tactic in a weed management strategy.

Conclusions

It is highly desirable that examples of system-based approaches to weed management in organic farming should become more common in the international scientific literature. One of the main reasons for the existence of this gap is possibly the conflict between the need for implementing long-term research (which is particularly important in an organic context) and the constraints posed by short-term research funding (Lockert, 2000). Additionally, researchers need to overcome their reluctance to carry out long-term studies, only partly arising from methodological difficulties. Modelling crop:weed interactions and weed population dynamics might help to bridge this gap (Kropff *et al.*, 2000), but model outputs would always have to be validated with results coming from ongoing long-term field experiments.

However, it should be stressed that 'reductionist' and 'holistic' research are not mutually exclusive; rather, they should complement each other. An ideal approach to weed management in organic farming should be one that includes two subsequent steps: (1) adjustment of the cropping system in order to reduce weed emergence and the abundance of selected troublesome species ('holistic' step); (2) fine-tuning of direct weed control methods (harrowing, hoeing, thermal weed control, etc.) within the scenario set up previously ('reductionist' step).

Last but not least, it should be kept in mind that, given the dynamic nature of agro-ecosystems, even optimized weed management systems would probably require some readjustment after a period of time; this is another reason why long-term, system-based experiments are particularly important in organic agriculture.

References

- ALTIERI MA (1995) Toward sustainable agriculture. In: *Agroecology The Science of Sustainable Agriculture* (ed. MA Altieri), 367–379. Westview Press, Boulder, CO, USA.
- ANAYA AL (1999) Allelopathy as a tool in the management of biotic resources in agroecosystems. *Critical Reviews in Plant Science* **18**, 697–739.

- ANDERSON WP (1999) *Perennial Weeds. Characteristics and Identification of Selected Herbaceous Species* (ed. WP Anderson). Iowa State University Press, Ames, IA, USA.
- ANDOW D (1991) Vegetational diversity and arthropod population response. *Annual Review of Entomology* **36**, 561–586.
- ANDREWS RW, PETERS SE, JANKE RR & SAHS WW (1990) Converting to sustainable farming systems. In: *Sustainable Agriculture in Temperate Zones* (eds CA Francis, CB Flora & LD King), 281–313. John Wiley & Sons, New York, USA.
- ANGELINI L, LAZZERI L, GALLETI S, COZZANI A, MACCHIA M & PALMIERI S (1998) Antigerminative activity of three glucosinolate-derived products generated by mirosinase hydrolysis. *Seed Science and Technology* **26**, 771–780.
- ASCARD J (1994) Dose–response models for flame weeding in relation to plant size and density. *Weed Research* **34**, 377–385.
- ASCARD J (1995) *Thermal Weed Control by Flaming*. PhD Thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden.
- ASCARD J & BELLINDER RR (1996) Mechanical in-row cultivation in row crops. In: *Proceedings 2nd International Weed Control Congress*, Copenhagen, Denmark, 1121–1126.
- ASCARD J, OLSTEDT N & BENGSSON H (1999) Mechanical weed control using inter-row cultivation and torsion weeders in vining pea. In: *Proceedings 11th EWRS Symposium*, Basle, Switzerland, 119.
- BÄRBERI P (2000) Il controllo integrato delle infestanti nelle colture orticole. *L'informatore Agrario* **21**, 91–97 (in Italian).
- BÄRBERI P & MAZZONCINI M (2001) Changes in weed community composition as influenced by cover crop and management system in continuous corn. *Weed Science* **49**, 491–499.
- BÄRBERI P, COZZANI A, MACCHIA M & BONARI E (1998a) Size and composition of the weed seedbank under different management systems for maize continuous crop. *Weed Research* **38**, 319–334.
- BÄRBERI P, CAPORALI F, CAMPIGLIA E & MANCINELLI R (1998b) Weed community composition in a mixed farming system in Central Italy. In: *Proceedings of the Workshop: Mixed Farming Systems in Europe* (eds H van Keulen, EA Lantinga & HH van Laar), A P Minderhoudhoeve-reeks no. 2, 71–77. Landbouuniversiteit Wageningen, Dronen, The Netherlands.
- BÄRBERI P, SILVESTRI N, PERUZZI A & RAFFAELLI M (2000) Finger harrowing of durum wheat under different tillage systems. *Biological Agriculture and Horticulture* **17**, 285–303.
- BÄRBERI P, BONARI E & MAZZONCINI M (2001) Weed density and composition in winter wheat as influenced by tillage systems. *Proceedings 1st World Congress on Conservation Agriculture*, Madrid, Spain, 451–455.
- BASTIAANS L & DRENT H (1999) Late-emerging weeds; phenotypic plasticity and contribution to weed population growth. In: *Proceedings 11th EWRS Symposium*, Basle, Switzerland, 3.
- BAUMANN DT, KROPPF MJ & BASTIAANS L (2000) Intercropping leeks to suppress weeds. *Weed Research* **40**, 359–374.
- BECKER K & BÖHRNSEN A (1994) Wirkungen mechanischer Pflegemaßnahmen auf die Unkrautabundanz und die N-mineralisation im Boden. *Zeitschrift für Pflanzkrankheiten und Pflanzschutz* **14**, 315–324 (in German with English abstract).
- BENVENUTI S & MACCHIA M (2000) Role of durum wheat (*Triticum durum* Desf.) canopy height on *Sinapis arvensis* L. growth and seed production. In: *Proceedings XIème Colloque International sur la Biologie des Mauvaises Herbes*, Dijon, France, 305–312.
- BERKOWITZ AR (1988) Competition for resources in weed-crop mixtures. In: *Weed Management in Agroecosystems: Ecological Approaches* (eds MA Altieri & M Liebman), 89–119. CRC Press, Boca Raton, FL, USA.
- BEVERIDGE LE & NAYLOR REL (1999) Options for organic weed control – what farmers do. In: *Proceedings 1999 Brighton Conference – Weeds*, Brighton, UK, 939–944.
- BLUM U, KING LD, GERIG TM, LEHMAN ME & WORSHAM AD (1997) Effects of clover and small grain cover crops and tillage techniques on seedling emergence of some dicotyledonous weed species. *American Journal of Alternative Agriculture* **4**, 146–161.
- BODYSTON RA & HANG A (1995) Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). *Weed Technology* **9**, 669–675.
- BONARI E & MACCHIA M (1975) Effetto dell'investimento sulla produzione del favino (*Vicia faba* L. var. *minor* Peterm Beck). *Rivista di Agronomia* **9**, 416–423 (in Italian with English abstract).
- BONTSEMA J, VAN ASSELT CJ & VERMEULEN GD (2000) Intra-row weed control. In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 55.
- BOULDIN DR, KLAUSNER SD & REID WS (1984) Use of nitrogen from manure. In: *Nitrogen in Crop Production* (ed. RD Hauck), 221–245. ASA-CSSA-SSSA, Wisconsin, USA.
- BOWMAN G (1997) *Steel in the Field: A Farmer's Guide to Weed Management Tools* (ed. G Bowman), Handbook Series no. 2. Sustainable Agriculture Network, Beltsville, USA.
- BUHLER DD (1999) Expanding the context of weed management. In: *Expanding the Context of Weed Management* (ed. DD Buhler), 1–7. The Haworth Press, New York, USA.
- BULSON HAJ, SNAYDON RW & STOPES CE (1990) Intercropping autumn-sown beans and wheat: effects on weeds under organic farming conditions. In: *Crop Protection in Organic and Low Input Agriculture* (ed. R Unwin), 55–62. British Crop Protection Council, Bracknell, UK.
- BULSON HAJ, WELSH JP, STOPES CE & WOODWARD L (1996) Agronomic viability and potential economic performance of three organic four year rotations without livestock 1988–1995. *Aspects of Applied Biology* **47**, *Rotations and Cropping Systems*, 277–286.
- CALDWELL B & MOHLER CL (2001) Stale seedbed practices for vegetable production. *Hortscience* **36**, 703–705.
- CHAMEN WCT (2000) A new methodology for weed control and cereal crop production based on wide span vehicles and precision guidance: Biotrac. In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 51–54.
- CLARK MS, FERRIS H, KLONSKY K, LANINI WT, VAN BRUGGEN AHC & ZALOM FG (1998) Agronomic, economic, and environmental comparison of pest management in conventional and alternative tomato and corn systems in Northern California. *Agriculture Ecosystems and Environment* **68**, 51–71.

- CONWAY GR (1987) The properties of agroecosystems. *Agricultural Systems* **24**, 95–117.
- COOK A & WOLFE M (2000) Production of organic seed for the organic farming sector. In: *Proceedings 13th International IFOAM Scientific Conference*, Basle, Switzerland, 218–221.
- COUSENS R & MOSS SR (1990) A model of the effects of vertical distribution of weed seeds within the soil. *Weed Research* **30**, 61–70.
- DE LUCA TH & DE LUCA DK (1997) Composting for feedlot manure management and soil quality. *Journal of Production Agriculture* **10**, 235–241.
- DI TOMASO JM (1995) Approaches for improving crop competitiveness through the manipulation of fertilization strategies. *Weed Science* **43**, 491–497.
- DITSCH DC, ALLEY MM, KELLEY KR & LEI YZ (1993) Effectiveness of winter rye for accumulating residual fertilizer N following corn. *Journal of Soil and Water Conservation* **48**, 125–132.
- DUKE SO, DAYAN FE, ROMAGNI JG & RIMANDO AM (2000) Natural products as sources of herbicides: current status and future trends. *Weed Research* **40**, 99–111.
- EGHBALL B & LESOING GW (2000) Viability of weed seeds following manure windrow composting. *Compost Science and Utilization* **8**, 46–53.
- EINHELLIG FA (1987) Interaction among allelochemicals and other stress factors of the plant environment. In: *Allelochemicals, Role in Agriculture and Forestry* (ed. GR Waller), 343–357. *ACS Symposium Series*, Vol. 330. American Chemical Society, Washington DC, USA.
- FOGELBERG F (1998) *Physical Weed Control – Intra-Row Brush Weeding and Photocontrol in Carrots*. PhD Thesis, Swedish University of Agricultural Sciences, Alnarp, Sweden.
- FOGELBERG F (2000) Electroporation – can we control weed seeds by the use of electric pulses applied in soil? In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 50.
- FOGELBERG F & DOCK GUSTAVSSON A-M (1999) Mechanical damage to annual weeds and carrots by in-row brush weeding. *Weed Research* **39**, 469–479.
- FROUD-WILLIAMS RJ (1983) The influence of straw disposal and cultivation regime on the population dynamics of *Bromus sterilis*. *Annals of Applied Biology* **103**, 139–148.
- FROUD-WILLIAMS RJ (1988) Changes in weed flora with different tillage and agronomic management systems. In: *Weed Management in Agroecosystems Ecological Approaches* (eds MA Altieri & M Liebman), 213–236. CRC Press, Boca Raton, FL, USA.
- GALLANDT ER, LIEBMAN M & HUGGINS DR (1999) Improving soil quality: implications for weed management. In: *Expanding the Context of Weed Management* (ed. DD Buhler), 95–121. The Haworth Press, New York, USA.
- GRIEPENTROG HW, WEINER J & KRISTENSEN L (2000) Increasing the suppression of weeds by varying sowing parameters. In: *Proceedings 13th International IFOAM Scientific Conference*, Basle, Switzerland, 173.
- GRUNDY AC, GREEN JM & LENNARTSSON M (1998) The effect of temperature on the viability of weed seeds in compost. *Compost Science and Utilization* **6**, 26–33.
- GUNSOLUS JL & BUHLER DD (1999) A risk management perspective on integrated weed management. In: *Expanding the Context of Weed Management* (ed. DD Buhler), 167–187. The Haworth Press, New York, USA.
- HAYMES R & LEE HC (1999) Competition between autumn and spring planted grain intercrops of wheat (*Triticum aestivum*) and field bean (*Vicia faba*). *Field Crops Research* **62**, 167–176.
- HEISEL T, SCHOU J, CHRISTENSEN S & ANDREASEN C (2001) Cutting weeds with a CO₂ laser. *Weed Research* **41**, 19–29.
- HOROWITZ M, REGEV Y & HERZLINGER G (1983) Solarization for weed control. *Weed Science* **31**, 170–179.
- HUTCHINSON CM (1999) *Trichoderma virens*-inoculated composted chicken manure for biological weed control. *Biological Control* **16**, 217–222.
- IAS (1996) International Allelopathy Society (IAS). Constitution and Bylaws. In: *Proceedings First World Congress on Allelopathy: A Science for the Future*, Cádiz, Spain.
- IKERD JE (1993) The need for a system approach to sustainable agriculture. *Agriculture Ecosystems and Environment* **46**, 147–160.
- INDERJIT (1996) Plant phenolics in allelopathy. *Botanical Review* **62**, 186–202.
- INDERJIT & DEL MORAL R (1997) Is separating resource competition from allelopathy realistic? *Botanical Review* **63**, 221–230.
- INDERJIT & KEATING KI (1999) Allelopathy: principles, procedures, processes, and promises for biological control. *Advances in Agronomy* **67**, 141–232.
- ISI (2001) *Current Contents*. Institute for Scientific Information, Philadelphia, USA.
- JIMENEZ-OSORNIO JJ & GLEISSMAN SR (1987) Allelopathic interference in a wild mustard (*Brassica campestris* L.) and broccoli (*Brassica oleracea* L. var. *italica*) intercrop agroecosystem. In: *Allelochemicals, Role in Agriculture and Forestry* (ed. GR Waller), 262–274. *ACS Symposium Series*, Vol. 330. American Chemical Society, Washington DC, USA.
- JORDAN NR, ZHANG J & HUERD S (2000) Arbuscular-mycorrhizal fungi: potential roles in weed management. *Weed Research* **40**, 397–410.
- JØRNSGÅRD B, RASMUSSEN K, HILL J & CHRISTIANSEN LJ (1996) Influence of nitrogen on competition between cereals and their natural weed populations. *Weed Research* **36**, 461–470.
- KARLEN DL, VARVEL GE, BULLOCK DG & CRUSE RM (1994) Crop rotations for the 21st century. *Advances in Agronomy* **53**, 1–45.
- KIELHORN A, DZINAJ T, GELZE F *et al.* (2000) Beikrautregulierung in Reihenkulturen – sensorgesteuerte Querhacke in Mais. *Zeitschrift für Pflanzkrankheiten und Pflanzschutz* **17**, 207–216 (in German with English abstract).
- KING LD (1984) Availability of nitrogen in municipal, industrial, and animal wastes. *Journal of Environmental Quality* **13**, 609–612.
- KROPFF MJ, BAUMANN DT & BASTIAANS L (2000) Dealing with weeds in organic agriculture – challenge and cutting edge in weed management. In: *Proceedings 13th International IFOAM Scientific Conference*, Basle, Switzerland, 175–177.
- KURSTJENS DAG & BLEEKER P (2000) Optimising torsion weeders and finger weeders. In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 30–32.

- KURSTJENS DAG & KROPFF MJ (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research* **41**, 211–228.
- KURSTJENS DAG, PERDOK UD & GOENSE D (2000) Selective uprooting by weed harrowing on sandy soils. *Weed Research* **40**, 431–447.
- LAL R, REGNIER E, ECKERT DJ, EDWARDS WM & HAMMOND R (1991) Expectations of cover crops for sustainable agriculture. In: *Cover Crops for Clean Water* (ed. WL Hargrove), 1–11. Soil and Water Conservation Society Publication, Ankey, USA.
- LAWSON HM & TOPHAM PB (1985) Competition between annual weeds and vining peas grown at a range of population densities: effects on the weeds. *Weed Research* **25**, 221–229.
- LEMERLE D, VERBEEK B, COUSENS RD & COOMBES NE (1996) The potential for selecting wheat varieties strongly competitive against weeds. *Weed Research* **36**, 505–513.
- LEMERLE D, VERBEEK B & ORCHARD B (2001) Ranking the ability of wheat varieties to compete with *Lolium rigidum*. *Weed Research* **41**, 197–209.
- LIEBMAN M & DAVIS AS (2000) Integration of soil, crop, and weed management in low-external-input farming systems. *Weed Research* **40**, 27–47.
- LIEBMAN M & DYCK E (1993) Crop rotation and intercropping strategies for weed management. *Ecological Applications* **3**, 92–122.
- LIGNEAU LAM & WATT TA (1995) The effects of domestic compost upon the germination and emergence of barley and six arable weeds. *Annals of Applied Biology* **126**, 153–162.
- LITTERICK AM, REDPATH J, SEEL W & LEIFERT C (1999) An evaluation of weed control strategies for large-scale organic potato production in the UK. In: *Proceedings 1999 Brighton Conference – Weeds*, Brighton, UK, 951–956.
- LOCKERETZ W (2000) Organic farming research, today and tomorrow. In: *Proceedings 13th International IFOAM Scientific Conference*, Basle, Switzerland, 718–720.
- MCCLOSKEY M, FIRBANK LG, WATKINSON AR & WEBB DJ (1996) The dynamics of experimental arable weed communities under different management practices. *Journal of Vegetation Science* **7**, 799–808.
- MAGDOFF F (1995) Soil quality and management. In: *Agroecology. The Science of Sustainable Agriculture* (ed. MA Altieri), 349–364. Westview Press, Boulder, CO, USA.
- MAYNARD A (1993) Nitrate leaching from compost-amended soils. *Compost Science and Utilization* **1**, 65–72.
- MELANDER B (1997) Optimization of the adjustment of a vertical axis rotary brush weeder for intra-row weed control in row crops. *Journal of Agricultural Engineering Research* **68**, 39–50.
- MELANDER B (2000) Mechanical weed control in transplanted sugar beet. In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 25.
- MELANDER B & RASMUSSEN K (2000) Reducing intrarow weed numbers in row crops by means of a biennial cultivation system. *Weed Research* **40**, 205–218.
- MOHLER CL (1996) Ecological bases for the cultural control of annual weeds. *Journal of Production Agriculture* **9**, 468–474.
- MOHLER CL & TEASDALE JR (1993) Response of weed emergence to rate of *Vicia villosa* Roth and *Secale cereale* L. residue. *Weed Research* **33**, 487–499.
- MT PLEASANT J & SCHLATER KJ (1994) Incidence of weed seed in cow (*Bos* spp.) manure and its importance as a weed source for cropland. *Weed Technology* **8**, 304–310.
- NISHIDA T, SHIMIZU N, ISHIDA M, ONOUE T & HARASHIMA N (1998) Effect of cattle digestion and of composting heat on weed seeds. *Japanese Agricultural Research Quarterly* **32**, 55–60.
- NORDELL A & NORDELL E (1998) A whole-farm approach to weed control. A strategy for weed-free onions. In: *Proceedings of the Conference: Sharing the Lesson of Organic Farming*, Guelph, Canada.
- NORRIS RF & KOGAN M (2000) Interactions between weeds, arthropod pests, and their natural enemies in managed ecosystems. *Weed Science* **48**, 94–158.
- OBERLE SL & KEENEY DR (1991) A case for agricultural systems research. *Journal of Environmental Quality* **20**, 4–7.
- OFORI F & STERN WR (1987) Cereal-legume intercropping systems. *Advances in Agronomy* **41**, 41–90.
- OLESEN JE, ASKEGAARD M & RASMUSSEN IA (2000) Design of an organic farming crop rotation experiment. *Acta Agriculturae Scandinavica – Section B, Soil and Plant Science* **50**, 13–21.
- OLOFSDOTTER M (2001) Rice – a step toward use of allelopathy. *Agronomy Journal* **93**, 3–8.
- OZORES-HAMPTON M, STOFFELLA PJ, BEWICK TA, CANTLIFFE DJ & OBREZA TA (1999) Effect of age of cocomposted MSW and biosolids on weed seed germination. *Compost Science and Utilization* **7**, 51–57.
- PAOLINI R, CAPORALI F & CAMPIGLIA E (1993) Yield response, complementarity and competitive ability of bread wheat (*Triticum aestivum* L.) and pea (*Pisum sativum* L.) in mixture. *Agricoltura Mediterranea* **123**, 114–121.
- PAOLINI R, PRINCIPI M, FROUD-WILLIAMS RJ, DEL PUGLIA S & BIANCARDI E (1999) Competition between sugarbeet and *Sinapis arvensis* and *Chenopodium album*, as affected by timing of nitrogen fertilization. *Weed Research* **39**, 425–440.
- PAUL JW & BEAUCHAMP EG (1993) Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. *Canadian Journal of Soil Science* **73**, 253–266.
- PEARSON CJ & ISON RL (1997) *Agronomy of Grassland Systems* (eds CJ Pearson & RL Ison). Cambridge University Press, Cambridge, UK.
- PENFOLD CM, MIYAN MS, REEVES TG & GRIERSON IT (1995) Biological farming for sustainable agricultural production. *Australian Journal of Experimental Agriculture* **35**, 849–856.
- PERUZZI A, BÄRBERI P, GINANNI M, RAFFAELLI M & SILVESTRI N (1997) Prove sperimentali di controllo meccanico delle infestanti del frumento mediante erpice strigliatore. In: *Proceedings VI Convegno Nazionale di Ingegneria Agraria*, Ancona, Italy, 669–678 (in Italian with English abstract).
- PUTNAM AR (1988) Allelochemicals from plants as herbicides. *Weed Technology* **2**, 510–518.
- QASEM JR & HILL TA (1989) On difficulties with allelopathy methodology. *Weed Research* **29**, 345–347.
- RASMUSSEN J (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. *Weed Research* **32**, 267–274.
- RASMUSSEN K (2000) Can slurry injection improve the selectivity of weed harrowing in cereals? In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 33–34.

- RASMUSSEN J & ASCARD J (1995) Weed control in organic farming systems. In: *Proceedings 13th Long Ashton International Symposium, Ecology and Integrated Farming Systems* (eds DM Glen, MP Greaves & HM Anderson), 49–67. John Wiley & Sons, Chichester, UK.
- RASMUSSEN K & RASMUSSEN J (2000) Barley seed vigour and mechanical weed control. *Weed Research* **40**, 219–230.
- RASMUSSEN IA, ASKEGAARD M & OLESEN JE (1999) Plant protection in organic crop rotation experiments for grain production. In: *Proceedings International Workshop on Designing and Testing Crop Rotations for Organic Farming*, Borris, Denmark, 321–330.
- RYDBERG NT & MILBERG P (2000) A survey of weeds in organic farming in Sweden. *Biological Agriculture and Horticulture* **18**, 175–185.
- SANCES FV & INGHAM ER (1997) Conventional and organic alternatives to methyl bromide on California strawberries. *Compost Science and Utilization* **5**, 23–37.
- SARTORATO I, ZUIN MC & ZANIN G (2001) I reflui zootecnici come veicolo d'infestazione dei campi coltivati. *L'Informatore Agrario* **7**, 31–36 (in Italian).
- SAUERBORN J, LINKE KH, SAXENA MC & KOCH W (1989) Solarization: a physical control method for weeds and parasitic plants (*Orobancha* spp.) in Mediterranean agriculture. *Weed Research* **29**, 391–397.
- SEIGLER DS (1996) Chemistry and mechanisms of allelopathic interactions. *Agronomy Journal* **88**, 876–885.
- SOIL ASSOCIATION (2000) *The Biodiversity Benefits of Organic Farming*. Soil Association, Bristol, UK.
- SPANDL E, DURGAN BR & FORCELLA F (1998) Tillage and planting date influence foxtail (*Setaria* spp.) emergence in continuous spring wheat (*Triticum aestivum*). *Weed Technology* **12**, 223–229.
- STEVENSON FC, LÉGÈRE A, SIMARD RR, ANGERS DA, PAGEAU D & LAFOND J (1998) Manure, tillage, and crop rotation: effects on residual weed interference in spring barley cropping systems. *Agronomy Journal* **90**, 496–504.
- STOLTON S, GEIER B & MCNEELY JA (2000) Introduction: the relationship between nature conservation, biodiversity and organic agriculture. In: *Proceedings International Workshop: the Relationship Between Nature Conservation, Biodiversity and Organic Agriculture* (eds S Stolton, B Geier & JA McNeely), Vignola, Italy, 5–12. IFOAM, Tholey, Germany.
- STONEHOUSE DP, WEISE SF, SHEARDOWN T, GILL RS & SWANTON CJ (1996) A case study approach to comparing weed management strategies under alternative farming systems in Ontario. *Canadian Journal of Agricultural Economics—Revue Canadienne d'Economie Rurale* **44**, 81–99.
- SWANTON CJ & WEISE SF (1991) Integrated weed management: the rationale and approach. *Weed Technology* **5**, 657–663.
- TEASDALE JR & MOHLER CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. *Agronomy Journal* **85**, 673–680.
- TEASDALE JR & MOHLER CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. *Weed Science* **48**, 385–392.
- TOMPKINS DK, CHAW D & ABIOLA AT (1998) Effect of windrow composting on weed seed germination and viability. *Compost Science and Utilization* **6**, 30–34.
- VAN DER WEIDE R & BLEEKER P (2000) Status of physical weed control in arable production and vegetables in The Netherlands. In: *Proceedings 4th Workshop of the EWRS Working Group on Physical and Cultural Weed Control*, Elspeet, The Netherlands, 1–2.
- VEREIJKEN PH, VISSER RP & KLOEN H (1998) *Innovatie van de EKO—Akkerbouw en Groenteteelt Met 10 Voorhoedebedrijven (1991–97)*. Rapport no. 88. AB-DLO, Wageningen, The Netherlands (in Dutch).
- WALLER GR, FENG MC & FUJII Y (1999) Biochemical analysis of allelopathic compounds: plants, microorganisms, and soil secondary metabolites. In: *Principles and Practices in Plant Ecology* (eds Inderjit, KMM Dakshini & CL Foy), 75–98. CRC Press, Boca Raton, FL, USA.
- WEIDENHAMER JD (1996) Distinguishing resource competition and chemical interference: overcoming the methodological impasse. *Agronomy Journal* **88**, 866–875.
- WELSH JP, PHILLIPS L, BULSON HAJ & WOLFE M (1999) Weed control strategies for organic cereal crops. In: *Proceedings 1999 Brighton Conference – Weeds*, Brighton, UK, 945–950.
- WESTON LA (1996) Utilization of allelopathy for weed management in agroecosystems. *Agronomy Journal* **88**, 860–866.
- WILSON BJ, WRIGHT KJ & BUTLER RC (1993) The effect of different frequencies of harrowing in the autumn or spring on winter wheat, and on the control of *Stellaria media* (L.) Vill., *Galium aparine* L. and *Brassica napus* L. *Weed Research* **33**, 501–506.
- YENISH JP, WORSHAM AD & CHILTON WS (1995) Disappearance of DIBOA-glucoside, DIBOA, and BOA from rye (*Secale cereale* L.) cover crop residue. *Weed Science* **43**, 18–20.
- ZANIN G, OTTO S, RIELLO L & BORIN M (1997) Ecological interpretation of weed flora dynamics under different tillage systems. *Agriculture Ecosystems and Environment* **66**, 177–188.
- ZIMDAHL RL (1993) Weed biology: reproduction and dispersal. In: *Fundamentals of Weed Science* (ed. RL Zimdahl), 59–89. Academic Press, San Diego, CA, USA.
- ZIMDAHL RL (1995) Weed science in sustainable agriculture. *American Journal of Alternative Agriculture* **10**, 138–142.