4 Cover Crops and Weed Management

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4.1 Introduction

The term 'cover crops' will be used in this chapter as a general term to encompass a wide range of plants that are grown for various ecological benefits other than as a cash crop. They may be grown in rotations during periods when cash crops are not grown, or they may grow simultaneously during part or all of a cash-cropping season. Various terms such as 'green manure', 'smother crop', 'living mulch' and 'catch crop' refer to specific uses of cover crops.

Cover crops have multiple influences on the agroecosystem (Sustainable Agriculture Network, 1998; Sarrantonio and Gallandt, 2003). They intercept incoming radiation, thereby affecting the temperature environment and biological activity at various trophic levels in the leaf canopy and underlying soils. They fix carbon and capture nutrients, thereby changing the dynamics and availability of nutrients. They reduce rain droplet energy and influence the overall distribution of moisture in the soil profile. They influence the movement of soils, nutrients and agrochemicals into and away from agricultural fields. They can change the dynamics of weeds, pests and pathogens as well as of beneficial organisms. Thus, the introduction of cover crops into the agroecosystem offers opportunities for managing many aspects of the system simultaneously. However, cover cropping also adds a higher level of complexity and potential interactions that may be more difficult to predict and manage.

This chapter addresses the complexity of managing cover crops in selected growing regions of the world. It focuses on the contributions that cover crops can make to weed management and the trade-offs that may be required between achieving weed management, crop production, and environmental benefits. Since cover crops can play a significant role in mitigating environmental impacts worldwide, interactions between weed management and management to enhance environmental protection will be emphasized.

4.2 Impact of Cover Crops on Weeds and Crops

Cover crop impact on weeds

Cover crops can influence weeds either in the form of living plants or as plant residue remaining after the cover crop is killed. Different weed life stages will be affected by different mechanisms depending on whether the cover crop is acting during its living phase or as post-mortem residue. Management of the cover crop may also be influenced by whether the goal is to suppress weeds during the living or post-mortem phases.

There is wide agreement in the literature that a vigorous living cover crop will suppress weeds growing at the same time as the cover crop

(Stivers-Young, 1998; Akobundu *et al.*, 2000; Creamer and Baldwin, 2000; Blackshaw *et al.* 2001; Favero *et al.*, 2001; Grimmer and Masiunas, 2004; Peachey *et al.*, 2004; Brennan and Smith, 2005). There is often a negative correlation between cover crop and weed biomass (Akemo *et al.*, 2000; Ross *et al.*, 2001; Sheaffer *et al.*, 2002). Table 4.1 lists the degree of weed suppression by live cover crops grown in different areas of the world. Generally, vigorous cover crop species such as velvetbean (*Mucuna* spp.), jack bean (*Canavalia ensiformis* (L.) DC.), cowpea (*Vigna unguiculata* (L.) Walp.), and sorghum-sudangrass (*Sorghum bicolor* (L.) Moench × *S. sudanense* (Piper) Stapf), which are well adapted to growth in hot climates, are effective smother crops in warm-season environments. Yellow sweetclover (*Melilotus officinalis* (L.) Lam.), a biennial cover crop, was effective at suppressing weeds during a 20-month fallow on the Canadian Great Plains (Blackshaw *et al.*, 2001). Annual cover crops more adapted to cool conditions such as rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* Roth) and various clovers (*Trifolium* spp.) are less effective as summer smother crops (Table 4.1). Many of these same cool-season species are more effective as winter annual cover crops (Peachey *et al.*, 2004); in fact, it is probably because of their effectiveness that there is so little literature documenting the suppression of winter weeds by these species. In Mediterranean climates with relatively mild winters, suppression of winter weeds may be more difficult, particularly with cover crops that often do not provide complete ground cover, such as subterranean clover (*Trifolium subterraneum* L.) and crimson clover (*Trifolium incarnatum* L.) in Italy (Barbari and Mazzoncini, 2001) or legume/oat (*Avena sativa* L.) mixes in central California (Brennan and Smith, 2005). Winter-killed cover crops such as mustard species (*Brassica* spp.) can establish quickly and suppress weeds during the autumn months but may allow spring weed establishment unless used preceding early spring cash crops (Grimmer and Masiunas, 2004).

Dead cover crop residue does not suppress weeds as consistently as live cover crops do (Teasdale and Daughtry, 1993; Reddy and Koger, 2004). The magnitude of weed suppression by residue is usually higher for weed emergence measured early in the season than for weed density or biomass measured later in the season. Table 4.2 outlines authors' estimates of the degree of weed suppression by living cover crops versus cover crop residue. Generally, living cover crops will suppress weeds more completely and at more phases of the weed life cycle than will cover crop residue. Some important mechanisms contrasting weed suppression by cover crop residue versus living cover crops are discussed below.

Cover crop residue can affect weed germination in soils through effects on the radiation and chemical environment of the seed. Cover crop residue on the soil surface can inhibit weed germination by creating conditions similar to those deeper in the soil, i.e. lower light and lower daily temperature amplitude (Teasdale and Mohler, 1993). Residue also can inhibit emergence by physically impeding the progress of seedlings from accessing light (Teasdale and Mohler, 2000) as well as by releasing phytotoxins that inhibit seedling growth (Yenish *et al.*, 1995; Blackshaw *et al.*, 2001). When fresh residue is incorporated into soils, decomposition processes can release pulses of phytotoxins or pathogens that inhibit germination and early growth of weeds (Dabney *et al.*, 1996; Blackshaw *et al.*, 2001; Davis and Liebman, 2003; Sarrantonio and Gallandt, 2003). Once seedlings become established, cover crop residue will usually have a negligible impact on weed growth and seed production or may even stimulate these processes through conservation of soil moisture and release of nutrients (Teasdale and Daughtry, 1993; Haramoto and Gallandt, 2005). Residue can provide a more favourable habitat for predators of weed seed on or near the surface of soils (Gallandt *et al.*, 2005); however, residue was found to have no effect on the survival of perennial structures or seeds in some experiments (Akobundu *et al.*, 2000; J.R. Teasdale *et al.*, unpublished data).

Live cover crops have a greater suppressive effect on all weed life cycle stages than cover crop residue (Table 4.2). A living cover crop absorbs red light and will reduce the red : far-red ratio sufficiently to inhibit phytochrome-mediated seed germination, whereas cover crop residue has a minimal affect on this ratio (Teasdale and Daughtry, 1993). A living cover crop competes with emerging and growing weeds for essential resources and inhibits

Table 4.1. Suppression of weeds that are growing at the same time as a live cover crop during summer or winter periods.

Period of growth	Location	Cover crop	Percentage weed biomass reduction[a]	Reference
Summer fallow	Nigeria	Velvetbean	85 (83–87)	Akobundu *et al.* (2000)
	Brazil savanna	Jack bean	72	Favero *et al.* (2001)
		Black mucuna	96	
		Lablab, pigeonpea	35 (22–48)	
	North Carolina, USA	Cowpea, sesbania, trailing soybean, buckwheat	85	Creamer and Baldwin (2000)
		Soybean, lablab	48	
		Sorghum-sudangrass, millet spp.	94	
	Maryland, USA	Hairy vetch	58 (52–70)	Teasdale and Daughtry (1993)
	Japan	Hairy vetch	66	Araki and Ito (1999)
		Wheat	39	
	Alberta, Canada	Yellow sweetclover	91 (77–99)	Blackshaw *et al.* (2001)
	Alberta, Canada	Berseem clover	58 (51–70)	Ross *et al.* (2001)
		Alsike, balansa, crimson, Persian, red, white clover	35 (9–56)	
		Rye	64 (31–89)	
Summer intercrop	Brazil (southern)	Black mucuna, smooth rattlebox	97 (95–99)	Skora Neto (1993)
		Jack bean, pigeonpea	83 (71–90)	
		Cowpea	39 (29–48)	
	Mississippi, USA	Hairy vetch	79	Reddy and Koger (2004)
	New York, USA	Rye	61 (37–76)	Brainard and Bellinder (2004)
	Norway	Subterranean, white clover	48 (45–51)	Brandsaeter *et al.* (1998)
Winter-surviving annuals	Oregon, USA	Rye	97 (94–99)	Peachey *et al.* (2004)
		Oats	89 (81–96)	
		Barley	89 (78–99)	
	Italy	Rye	83 (54–99)	Barbari and Mazzoncini (2001)
		Subterranean, crimson clover	32 (0–67)	
Winter-killed annuals	New York, USA	Oilseed radish, mustard	94 (81–99)	Stivers-Young (1998)
		Oats	71 (19–95)	
	Michigan, USA	Annual medics, berseem clover	54 (18–88)	Fisk *et al.* (2001)
	Illinois, USA	Mustard	93	Grimmer and Masiunas (2004)
		Barley	94	
		Oats	76	

[a] Mean percentage reduction relative to a control without cover crop. Data that summarizes more than one year and/or location are presented with the range shown in parentheses. Where cover crop management treatments were included in the research, conditions that represented the optimum growth of the cover crop were chosen for this summary.

Table 4.2. Potential impact of typical cover crop residue or live cover crop on inhibition of weeds at various life cycle stages.

Weed life cycle stage	Cover crop residue	Live cover crop
Germination	Moderate	High
Emergence/establishment	Moderate	High
Growth	Low	High
Seed production	Low	Moderate
Seed survival	None?[a]	Moderate?[a]
Perennial structure survival	None?[a]	Low–moderate?[a,b]

[a] More research is needed to provide definitive estimates of cover crop influences on these processes.
[b] When cover crops are combined with other practices such as soil disturbance or mowing, perennial structure survival may be more effectively reduced, as discussed in Dock Gustavsson (1994) and Graglia *et al.* (2006).

emergence and growth more than cover crop residue does (Teasdale and Daughtry, 1993; Reddy and Koger, 2004). If growth suppression is sufficient, a live cover crop can also inhibit weed seed production (Brainard and Bellinder, 2004; Brennan and Smith, 2005). Weed seed predation at the soil surface was higher when living cover crop vegetation was present (Davis and Liebman, 2003; Gallandt *et al.*, 2005), suggesting a role for living cover crops in enhancing weed seed mortality.

Cover crop impact on perennial and parasitic weeds

Perennial weeds are often better competitors, and are more difficult to control with cover crops than annual weeds are, because of larger nutritional reserves and faster rates of establishment. However, several reports have shown the capability for suppressing perennial weeds with living cover crops during fallow periods. Blackshaw *et al.* (2001) found that yellow sweetclover controlled dandelion (*Taraxacum officinale* Weber ex Wiggers) and perennial sowthistle (*Sonchus arvensis* L.) as well as several annual weeds in Canada. Cultivation in combination with a competitive cover crop controlled important perennial weeds such as quackgrass (*Elytrigia repens* (L.) Nevski), perennial sowthistle and Canada thistle (*Cirsium arvense* (L.) Scop.) in cereal-dominated rotations in Scandinavia (Håkansson, 2003). Cover-cropping systems will probably be most effective if maximum disturbance of, or competition with, perennial weeds occurs at the compensation point which may be defined as that time where the source–sink dynamic of carbohydrate reserves shifts from the underground organs as the source and the above-ground organs as the sink, to the reverse (Håkansson, 2003).

Many regions of Africa have heavy infestations of aggressive perennial weeds that multiply by seeds and rhizomes, such as cogongrass (*Imperata cylindrica* (L.) Beauv.), bermudagrass (*Cynodon dactylon* (L.) Pers.) and sedges (*Cyperus* spp.). Farmers cannot produce crops economically and have abandoned their fields when these weeds are not controlled. To overcome these constraints, various cover-crop species were evaluated under on-farm conditions, and up to 90% weed reduction was achieved (Taimo *et al.*, 2005). The results obtained in several districts in Sofala Province, Mozambique, with the use of black and grey mucuna (*Mucuna pruriens* (L.) DC.), calopo (*Calopogonium mucunoides* Desv.), sunn hemp (*Crotalaria juncea* L.), jack bean and Brazilian jack bean (*Canavalia brasiliensis* Mart. ex Benth.) are very encouraging and showed that they effectively suppressed bermudagrass, sedges and cogongrass. After cleaning the fields, farmers saved on labour time/costs and were able to grow soybean (*Glycine max* (L.) Merr.), beans and cereals successfully. Generally, live cover crops that establish an early leaf canopy cover are most competitive with weeds. Akobundu *et al.* (2000) found that development of early ground cover was more important than the quantity of dry matter produced for suppression of cogongrass by velvetbean accessions.

Some of Africa's worst agricultural pests are parasitic weeds, including witchweed (*Striga* *asiatica* (L.) Ktze.) Normally, the severity of these parasitic weeds is highly linked with continuous monocropping and also with soil fertility depletion. These weeds withdraw resources from the crop and, consequently, lead to very low crop yields. This means that measures to shift from the common practice of monocropping to crop rotation and enhanced soil organic matter and fertility must be implemented. Soil management that aims to increase soil fertility by crop rotation has included the use of the cover crops tropical kudzu (*Pueraria phaseoloides* (Roxb.) Benth.) and calopo (Table 4.3). Tropical kudzu was the best option to control witchweed in northern Ivory Coast. Velvetbean and some varieties of cowpea safely reduced the population of witchweed and eradicated it after two seasons (Calegari *et al.*, 2005a).

Cover crop impact on crops

Crops respond to cover crops in many of the same ways as weeds do. Numerous reports have documented that live cover crops that are competitive enough to suppress weeds will also suppress a cash intercrop. Brandsæter *et al.* (1998) showed that a white clover (*Trifolium repens* L.) or subterranean clover living mulch suppressed both weeds and cabbage (*Brassica oleracea* L. convar. *capitata* (L.) Alef.). Sheaffer *et al.* (2002) found that annual medic (*Medicago* spp.) living mulch and weed growth were inversely related, but they also found an inverse relationship between medic growth and soybean yield. Maize (*Zea mays* L.) grain yield was reduced by several annual legumes intercropped with maize for autumn forage (Alford, 2003) or by a hairy vetch living mulch (Reddy and Koger, 2004). Regrowth from a rye cover crop that was not adequately killed before planting a cash crop also reduced crop growth (Brainard and Bellinder, 2004; De Bruin *et al.*, 2005; Westgate *et al.*, 2005). Generally, crop suppression by living cover crops is the result of competition for essential resources.

Cover crop residue can suppress cash crop growth for many of the same reasons as weeds are suppressed by residue. Residue can interfere with crop establishment by physically interfering with seed placement in the soil, by maintaining cool soils, by releasing phytotoxins, or by enhancing seedling diseases (Dabney *et al.*, 1996, Davis and Liebman, 2003; Gallagher *et al.*, 2003; Westgate *et al.*, 2005). Reduced growth of crops in cover crop residue, particularly small-grain cover crops, has been associated with reduced availability of nitrogen, release of phytotoxins, and cooler soils (Norsworthy, 2004; Westgate *et al.*, 2005). On the other hand, cover crop residue on the soil surface has the capability of stimulating crop growth because of retention of soil moisture by a surface mulch (Araki and Ito, 1999; Gallagher *et al.*, 2003) and maintenance of cooler soils in a hot mid-season environment (Araki and Ito, 1999; Hutchinson and McGiffen, 2000). Also, legume cover crops can stimulate crop growth by increased availability of nitrogen (Gallagher *et al.*, 2003; Sarrantonio and Gallandt, 2003; Calegari *et al.*, 2005b) and promotion of genes that delay senescence and enhance disease resistance (Kumar *et al.*, 2004).

Table 4.3. Effect of cover crops on witchweed infection and maize yield in Africa.

Cover crop species	Maize plants infested by witchweed (%)	Maize yield (kg/ha)
Pueraria phaseoloides	3	2540
Calopogonium mucunoides	4	2260
Cassia rotundifolia	18	2310
Macroptilium atropurpureum	98	1250
Centrosema pubescens	100	1120
Tephrosia pedicellata	100	910
Control	100	730

Source: Charpentier *et al.* (1999).

4.3 Cover Crop Uses in Selected Climatic Regions

Northern temperate regions

The climate within this region is characterized by freezing winters and relatively cool and short summers (e.g. most areas in northern Europe and Canada), but this may be modified by latitude and distance from the coast. The opportunity to grow cover crops other than during the cash-cropping season decreases in northern and inland directions. In southern and coastal areas of this region (e.g. Denmark and southern Sweden), cover crops can be established after a cash crop is harvested (Thorup-Kristensen *et al.*, 2003). Sowing cover crops after early-harvested cash crops, such as early cultivars of potatoes (*Solanum tuberosum* L.) and vegetables, is also possible at locations with a short growing season. Danish studies have focused on root growth dynamics where specific catch crops are coupled to specific subsequent cash crops for two purposes: (i) optimal transfer of plant nutrients from year to year; and (ii) plant nutrient release in the most advantageous soil layer for the subsequent cash crop during the following year (Thorup-Kristensen *et al.*, 2003). The main purpose of using cover crops in northern regions has traditionally been to prevent erosion and nutrient leaching or for green manuring, but the focus on weed control in cover crop systems is increasing as well. We will focus on two commonly used cover crop systems in the region – undersown green manure and catch crops in cereals, and annual green manure cover crops in rotation with cash crops.

The most common cover crop practice in the Scandinavian region is undersowing of clover or clover–grass as a green manure (organic farms), or grass as a catch crop (conventional and organic farms) in cereals. When management is optimized for: (i) cereal and cover crop species and cultivar; (ii) sowing time and seeding rates of the cover crop; and (iii) soil fertility, there are often small or insignificant negative cover crop impacts on crop yield in these systems (Breland, 1996; Olesen *et al.*, 2002; Molteberg *et al.*, 2004). However, cereal yield depression because of competition from undersown cover crops has been reported (Korsaeth *et al.*, 2002). Experiments in Norway have shown that pure stands of cereals are often outyielded by cereals undersown with white clover by as much as 500–1000 kg/ha in stockless cereal-dominated organic farming rotations (Henriksen, 2005). Studies in Norway have shown that ryegrass (*Lolium* spp.) as a catch crop established through undersowing in cereals retains 25–35 kg N/ha in the autumn (Molteberg *et al.*, 2004). Several studies have demonstrated that undersown green manure or catch crops reduce weed biomass (Hartl, 1989; Breland, 1996). The significance of undersown cover crop impacts on weed growth depends on whether the results are compared with an untreated control or with different levels of other treatments such as weed harrowing. A Danish study indicated that undersown cover crops gave equivalent weed control to low-intensity weed harrowing in plots without undersown cover crops; however, high-intensity weed harrowing gave better weed control than did cover crops (Rasmussen *et al.*, 2006). Although it is expected that a living cover crop may inhibit weed seedlings emerging from seed more than shoots from perennial storage organs (see Table 4.2), Dyke and Barnard (1976) found that Italian ryegrass (*Lolium multiflorum* Lam.) and red clover (*Trifolium pratense* L.) undersown in barley (*Hordeum vulgare* L.) suppressed quackgrass by more than 50% compared with barley alone. However, the promising result of this study may have been influenced by the reduction in the competitive ability of quackgrass because rhizomes were transplanted at a depth of 20 cm, which is much deeper than these organs normally reside. Preliminary results from Norway (L.O. Brandsæter *et al.*, unpublished data) indicate that red clover undersown in oat reduces the biomass of established stands of perennial sowthistle (*Sonchus arvensis* L.), and to some degree quackgrass, but does not suppress established stands of Canada thistle (*Cirsium arvense* (L.) Scop.). Rasmussen *et al.* (2005) has hypothesized that, because undersown cover crops keep plant nutrients in the upper soil layer, their presence favours crops with shallow roots over Canada thistle, which has deeper roots. Thus, the use of cover crops undersown in cereals may both increase crop nutrient supply for the subsequent crop in the rotation and decrease the growth of weeds. However, the use of cover crops also jeopardizes the use of mechanical weed control because farmers cannot weed-harrow in the crop after sowing the cover crop, and a growing cover crop in the autumn obstructs stubble cultivation for quackgrass control (Rasmussen *et. al.*, 2005), which is otherwise a standard non-chemical method for controlling this weed.

In Nordic organic stockless farming, the use of one entire growing season for a green manure cover crop is a common practice for many purposes, the most important of which are adding nitrogen to the soil and controlling perennial weeds. Generally, a 1-year green manure cover crop can be introduced into a cropping system by undersowing clover–grass in cereals the previous year (as described above), or by sowing the cover crop in the spring. One advantage of undersowing in the previous year is that few weeds will emerge in the spring after the green manure is established. Studies have shown that the soil weed seed bank decreases when this method is used (Sjursen, 2005). On the other hand, sowing the green manure crop in spring or early summer provides an opportunity for a period of soil cultivation in the autumn and/or spring before sowing the green manure cover crop. Fragmentation of roots or rhizomes by soil cultivation, followed by deep ploughing, is a classical approach for controlling perennial weeds (Håkansson, 2003). Furthermore, in classic experiments (Fig. 4.1), soil cultivation and ploughing followed by a competitive cash crop or cover crop has shown promising effects on quackgrass (Håkansson, 1968), perennial sowthistle (Håkansson and Wallgren, 1972) and Canada thistle (Thomsen *et al.*, 2004). This may offer a good approach for non-chemical control of creeping perennial weeds in cereal-dominated rotations, but additional research is needed in order to optimize these methods.

Generally, cover crop competition for 1 year alone is not sufficient to satisfactorily suppress perennial weeds such as Canada thistle and perennial sowthistle. These weeds also have to be mowed frequently at specific stages of development. Mechanical disturbance for weakening a perennial weed plant is theoretically most effective when the plant has reached the stage with minimum reserves in underground storage structures, although more research is needed to more readily identify these stages (see overview in Håkansson, 2003). Factorial experiments are required to separate the effects of cover crop competition from the effects of mowing, and to determine potential interactions between mechanical and cover crop effects. In a field study conducted by Dock Gustavsson (1994) comparing times of 1 week and 5 weeks between mowing treatments, it was shown that Canada thistle growing in a red clover cover crop should preferably be mowed at intervals of 4 weeks to obtain the best suppression of the thistle without killing the red clover cover crop. More frequent mowing killed the clover plants or damaged them severely. The author also concluded that mowing in the spring and early summer suppressed weed growth more than mowing at later dates. In similar studies in Denmark with mixtures of white clover and grass as cover crops, Graglia *et al.* (2006) demonstrated an inverse linear relationship between the number of mowing passes up to six times between mid-May to late July and the above-ground biomass of Canada thistle in the subsequent year. The correlation between the weed control level and the yield of spring barley during the year following cover cropping was, however, not always positive. The reason was probably that mowing not only influenced weed growth but also the cover crop's ability to add

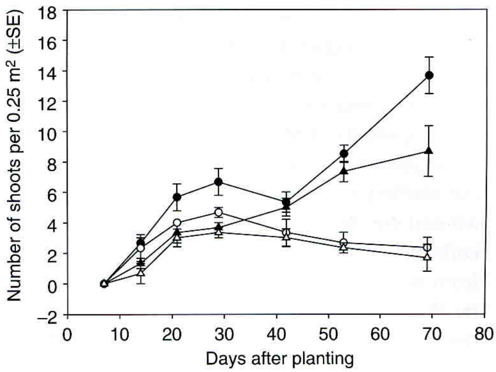

Fig. 4.1. Influence of root fragment length: 5-cm (triangles) vs 10-cm root pieces (circles); and competition: with (empty symbols) vs without cover crop (filled symbols) on the number of shoots of Canada thistle per 0.25 m^2. The root fragments were transplanted at a depth of 5 cm. Vertical bars represent standard error (SE). (*Source:* Thomsen *et al.*, 2004.)

nitrogen to the cropping system. Graglia *et al.* (2006) concluded that the presence of clover–grass cover crops strongly decreased the above-ground biomass of Canada thistle, presumably by suppressing the regrowth of shoots in the late-summer and autumn period that followed the ending of the mowing treatments. Hence, we can conclude that a continuous depletion of carbohydrates from the root system, resulting from a joint effect of mowing and competition by the cover crop, will decrease the regrowth capacity of Canada thistle as well as other perennials such as quackgrass and perennial sowthistle.

Warmer temperate regions

In this section we discuss the use of cover crops in regions characterized by cold, usually freezing, winters but with longer and warmer summers than in the northern regions discussed above (e.g. most areas of the USA, southern Europe, and Japan). In these regions there are suitable conditions for planting and growing winter annual cover crops after a cash crop is harvested in late summer/autumn and before the next cash crop is planted the following spring. Adapted species have the capability of: (i) reliably producing a uniform stand of established plants in autumn before the onset of cold weather; (ii) surviving freezing weather during winter; and (iii) rapidly growing during cool conditions in spring before planting a cash crop. Growth of a cover crop during this period has the advantage that summer annual weed species established before cover crop planting are destroyed by planting operations and those that become established after planting will be winterkilled. The only troublesome weed species that establish with winter annual cover crops are winter annuals and perennials that continue growth after the cover crop is terminated and the cash crop is planted. Typically, vigorous and well-adapted cover crops such as rye or hairy vetch will provide complete ground cover and be highly competitive, leaving relatively few weeds at the time of planting a spring crop.

Rye is a commonly used cover crop that is grown before summer annual cash crops and is representative of the use of small-grain cover crops in general. Rye can provide many benefits, including protecting the environment from loss of sediments, nutrients and agrochemicals (Sustainable Agriculture Network, 1998; Sarrantonio and Gallandt, 2003). It protects soils from water and wind erosion during the winter months and captures nutrients that may be leached during rainy periods when the soil is not frozen. If rye is terminated and the residue is left on the soil surface in conservation tillage systems, it can protect the environment from water and wind erosion during the period of crop establishment as well as from runoff losses of nutrients and agrochemicals. Other advantages include allowing earlier entry to fields in spring than would be possible with tilled soil. Long-term benefits include the sequestration of carbon and maintenance of soil organic matter, with related benefits for soil quality.

Residue of rye or other small-grain cover crops remaining on the soil surface after cover crop termination can suppress weed emergence and biomass in subsequent crops, particularly in the absence of herbicide (Kobayashi *et al.*, 2004; Norsworthy, 2004). When rye termination was delayed, resulting in more residue biomass, greater weed suppression was achieved (Ashford and Reeves, 2003; Westgate *et al.*, 2005). However, rye and small-grain cover crops also have been shown to reduce crop stands and yields because of interference with proper seed placement, cooler soils, and the release of phytotoxins from decomposing residue (Reddy, 2001; Norsworthy, 2004; Westgate *et al.*, 2005). Interseeding rye or small-grain cover crops tended to provide higher levels of weed suppression when interseeded at or near planting, but also tended to reduce crop yields under these conditions (Rajalahti *et al.*, 1999; Brainard and Bellinder, 2004). Generally, management that increased weed suppression also tended to increase the risk of crop yield reductions. Weed suppression by rye or other small-grain cover crops without herbicide usually was not adequate on its own, and herbicide programmes were required in order to achieve maximum crop yield (Rajalahti *et al.*, 1999; Reddy, 2001; Gallagher *et al.*, 2003; Norsworthy, 2004; De Bruin *et al.*, 2005). These results suggest that management of rye or small-grain cover crops should focus on optimization of the environmental rather than the weed-suppressive benefits of these cover crops.

Winter annual legume species represent another important group of cover crops in temperate climates. Hairy vetch is the most winter-hardy and reliable winter annual legume and is used primarily because of potential benefits to soil fertility (Sustainable Agriculture Network, 1998; Sarrantonio and Gallandt, 2003). The most important benefit is the release of nitrogen from killed vegetation to subsequent cash crops and the significant reduction in fertilizer nitrogen requirements. For this reason, it is often used preceding crops with a high nitrogen requirement such as maize or tomatoes. Hairy vetch mulch on the soil surface in no-tillage systems has increased soil moisture availability to crops during summer by increasing infiltration of rain and preventing evaporation on drought-prone soils. It also has been shown to trigger expression of genes that delay senescence and enhance disease resistance in tomatoes (Kumar *et al.*, 2004) and to suppress certain pests, pathogens and weeds.

The impact of hairy vetch on weed emergence depends on many factors. Higher than naturally produced biomass levels on the soil surface (>5 t/ha of dry residue) can inhibit the emergence of many annual weed species. At naturally produced levels (usually 3–5 t/ha of dry residue), weed emergence may be suppressed, unaffected or stimulated, depending on species and conditions (Teasdale and Mohler, 2000). Araki and Ito (1999) showed a high level of weed suppression by hairy vetch residue in Japan. However, typically there is, at best, a temporary suppression of early emergence but little long-term control. The leguminous nature of this residue (low C:N ratio) results in more rapid degradation and less suppressive amounts of residue over time than rye residue (Mohler and Teasdale, 1993). Also, the release of inorganic nitrogenous compounds can trigger germination and stimulate emergence of selected weeds, e.g. *Amaranthus* spp. (Teasdale and Pillai, 2005). Attempts to allow hairy vetch to continue growth as a living mulch during early growth of cash crops have provided improved weed control but have also proved detrimental to crop populations, growth and yield (Czapar *et al.*, 2002; Reddy and Koger, 2004). Generally, as with a rye cover crop, most research shows that hairy vetch does not provide reliable full-season weed control and must be combined with additional weed management options, usually herbicides, in order to achieve acceptable control.

Many research projects have investigated the influence of cover crops in a factorial with other management practices. In most cases, management has a bigger influence on weed control than cover crops do. Barbari and Mazzoncini (2001) conducted a long-term factorial study of cover crops and management systems, including tillage and herbicide factors. They found that weed abundance was influenced most by management system rather than cover crop, although cover crop did influence weed community composition within a low-input, minimum-tillage management system. Swanton *et al.* (1999) determined that tillage was more important than nitrogen rate or a rye cover crop in having a long-term influence on weed density or species composition in a maize crop. Peachey *et al.* (2004) showed by variance partitioning that primary tillage was much more important than cover crop in regulating weed emergence in vegetable crops. Since minimum-tillage agriculture can make many important contributions to preserving and building soil quality and fertility, management of cover crops to enhance soil-building and environmental contributions to minimum-tillage systems appears to be more important than management for weed suppression in temperate cropping systems.

Organic production systems have become an increasingly important segment of agriculture in recent years. In the absence of herbicide and fertilizer products, cover crops play a more important role for weed management and fertility in organic than in conventional farming. Legumes are necessary cover crops, either alone or in mixtures, because of the need to produce nitrogen as part of the on-farm system. The use of living legume cover crops to suppress weeds during fallow periods can be successful (Blackshaw *et al.*, 2001; Fisk *et al.*, 2001; Ross *et al.*, 2001). This may be most important to organic weed management as a means to reduce weed seed production and accelerate weed seed predation within rotational programmes. The use of cover crops in minimum-tillage organic crop production is a worthy objective in order to realize the environmental benefits of both reduced tillage and organic farming, but it can be problematic on organic farms for several reasons. Mechanical implements must be used to terminate cover crops and the results can be inconsistent; however, cover crops mowed or rolled at flowering can be killed more effectively than when operations are performed while the cover crop remains vegetative (Ashford and Reeves, 2003; Teasdale and Rosecrance, 2003; De Bruin *et al.*, 2005). As discussed earlier, residue on the soil surface will not consistently control weeds over a full season. Mechanical removal of weeds with a higher-residue cultivator has been shown to be less efficient in minimally tilled than in previously tilled soil (Teasdale and Rosecrance, 2003), thereby reducing the capacity for effective post-emergence weed control in minimum-tillage organic systems. The success of high-residue cover crop systems will depend on effective residue management to alleviate interference with crop production while maximizing interference with weed growth.

Subtropical/tropical South America

Agricultural conditions in warmer regions with potentially high rainfall make it difficult to maintain soil organic matter and to retain residue on the soil surface. Weed, nematode and pest populations can grow without interruption throughout the year. Bare soil is exposed to high levels of erosion from heavy rainfall, and soils can warm to temperatures that suppress productive root and biological activity. Cover crops can play an important role in alleviating all of these problems.

Concern over preserving soil and water in Brazil was not a priority until the 1970s. With the spread of annual crop production, monocultures, and tractor mechanization (which almost doubled in Paraná State in the 1970s), and with practically no conservation methods used, there was an acceleration of erosion and a decrease in organic matter and nutrients. This gave impetus to soil and water preservation efforts. The no-tillage system that has been developed includes the use of different species of cover crops and crop rotation as fundamentals in the structure of rational and sustainable management for annual crops. Almost all the advantages of the no-tillage system come from the permanent cover of the soil. Cover crops are planted primarily to protect the soil from the direct impact of raindrops. Protection is given by the growing plants themselves as well as by their residues. A total cover of the soil with plant residues improves the infiltration of rainfall. At the same time, cover crops have the potential to improve soil fertility as green manure cover crops.

The use of cover crops and crop rotation, as well as permanent no-tillage, are the key factors for the unprecedented growth of no-tillage, especially in Brazil and Paraguay. Only those farmers who have understood the importance of these practices are obtaining the highest economic benefits from this system. The systematization of these practices through work in hydrological micro-basins has advanced to a point where these systems occupy more than 5.2 million ha in Paraná, and about 23 million ha in Brazil. Controlled studies conducted on the St Antonio farm in Floresta, North Paraná (500 ha), comparing both tillage systems on a cultivated area of 1.6 ha over a 6-year period, found that no-till systems yielded approximately 34% more soybeans and 14% more wheat (*Triticum aestivum* L.) than did conventional tillage systems. Growing these crops in rotation with cover crops rather than as a monoculture added 19% and 6%, respectively, to soybean and wheat yields (Calegari *et al.*, 1998). A separate study on a 50 ha experimental site in North Paraná gave further evidence that a well-designed no-till system with soybeans in crop rotation can generate net income gains compared with conventional systems. Soybean production in a no-till system resulted in a US$3960 increase in revenue based on higher yields, and US$4942 in savings on machinery, fuel, labour and fertilizer compared with conventional tillage, resulting in a total benefit of US$8902 from 50 ha (Calegari *et al.*, 1998). Thus, experimental results and farmers' practices in the tropics and temperate climates have shown the important effects of cover crop use, crop rotation and no-tillage production to improve soil properties, increase crop yields, and contribute to biodiversity and environmental equilibrium.

The most common cover crop species are black oats (*Avena strigosa* Schreb.) in subtropical areas and pearl millet (*Pennisetum americanum* (L.) Leeke) in tropical areas. The most frequent species used for mixtures with black oats are vetch (*Vicia* spp.), lupin (*Lupinus* spp.)

or radish (*Raphanus sativus* L.). Facility of seed production (and therefore lower price and greater availability on the market), good biomass production, and minimal input requirements are the reasons that farmers prefer black oats and pearl millet as cover crop species. They have good tolerance to pests and diseases and can grow in low-fertility conditions. Black oats are used on about 3.2 million ha in the states of Paraná and Rio Grande do Sul, Brazil, and on about 300,000 ha in Paraguay, mainly in mechanized farming systems.

One important characteristic of cover crops is their ability to suppress and smother weeds. Favero *et al.* (2001) found that cover crops modified the dynamics of weed species occurrence. Weed populations were reduced by different amounts depending on cover crop mass and species (Severino and Christoffoleti, 2004). Skora Neto and Campos (2004) demonstrated the effect of fallow period and the suppressive effect of cover crops on succeeding weed populations. In a period of 3 years, a weed population of 136 plants/m^2 was reduced to 9 plants/m^2 when cover crops were used during fallow periods (Fig. 4.2). One important aspect of a weed management programme is not leaving a niche between the harvesting of a crop and the sowing of the next, in which weeds are able to establish. The occupation of space during fallow is important not only during crop development, but also during the intervals between them. The use of cover crops in these intervals has a profound effect on weed populations; otherwise, fallow periods allow weeds to capture space and to replenish the seed bank.

Another option to maintain ground cover and produce more cash crops in the rotation is intercropping with cover crops. In small-scale farming, maize is one crop in which this operation is practised; cover crops suitable for intercropping are jack bean, dwarf pigeonpea (*Cajanus cajan* (L.) Millsp.) and showy rattlebox (*Crotalaria spectabilis* Roth). They are used primarily as a green manure; however, their smothering effect also provides good weed suppression at the harvest and postharvest stages of maize (Skora Neto, 1993).

Cover crop residues can also be effective for suppressing weeds through physical and allelopathic mechanisms. Mulch from cover crop species with high biomass production and with

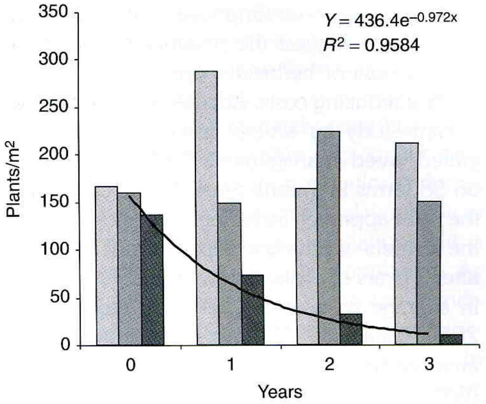

Fig. 4.2. Weed population change during three years with autumn and winter fallow (no cover crops; light grey), autumn fallow (cover crop in winter; dark grey), and without fallow (cover crop in autumn and winter; black). Solid line shows exponential decay for treatment without fallow. (*Source:* Skora Neto and Campos, 2004.)

slow decomposition (higher C:N ratio) are more effective for weed population reduction. Almeida and Rodrigues (1985) demonstrated a 2.5 t/ha weed biomass reduction for each 1.0 t/ha dry biomass of residues on the soil surface (Fig. 4.3). Soil tillage also affects weed density. Almeida (1991), verified, at 63 days after preparing the soil, that the weed infestation in conventional tillage (ploughing and harrowing) was 187% higher than with no tillage. The cumulative effect of absence of tillage and presence of mulching (physical and allelopathic effects) can be an important integrated strategy for reducing weed populations.

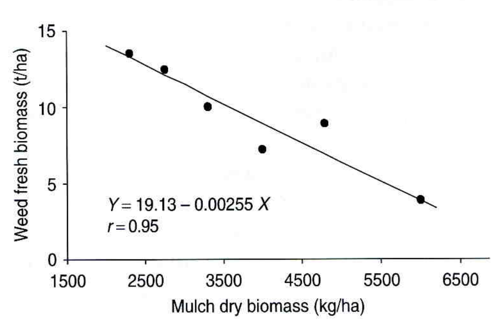

Fig. 4.3. Correlation between mulch dry biomass (kg/ha) and weed fresh biomass (t/ha) 85 days after mulch formation. (*Source:* Almeida and Rodrigues, 1985.)

Results demonstrating weed suppression by cover crops suggest the possibility of reducing the amounts of herbicides applied, and consequently reducing costs. Adegas (1998) describes a joint study by several institutes of an integrated weed management (IWM) programme on 58 farms in Parana State, Brazil, comparing the IWM approach including cover crops against the farmers' weed-control practices. The results after 3 years of evaluation were a 35% decrease in average costs and a herbicide reduction of 25%. Bianchi (1995) shows that, across 34 local areas at Rio Grande do Sul State, Brazil, the IWM programme reduced weed control costs by 42% compared with farmers' practices. These results demonstrate the agronomic, economic and ecological viability of IWM including cover crops.

Although a reduction in herbicide use has been observed on farms where good no-tillage practices are used, the total elimination of herbicides in crop production seems difficult, especially on large-scale farms. For small farms, where labour is available and the weed density is low, it is possible. To eliminate the herbicides before planting it is necessary to use cover crops that can be managed mechanically (knife-rolled). For example, oats, rye, radish, lupin and sunn hemp are some species that can be rolled down during the stage of seed formation without regrowing and which will form an effective mulch without herbicide. During the crop season, however, it is necessary to rely on manual labour and that can be time-consuming and full of drudgery. Skora Neto *et al.* (2003), in a study carried out at the farm level, verified the possibilities of no-tillage without herbicides; the constraint was the labour requirements for weed control. Areas with low weed populations were more suitable for no-tillage without herbicide. Skora Neto and Campos (2004) measured the hoeing time in two weed populations. With a high weed population (180 plants/m^2), hoeing time was 231 h/ha, and at low weed density (9 plants/m^2) it was 71 h/ha.

To overcome the constraints of labour requirements in no-till systems, Almeida (1991) recommends avoiding weed seed production as a way of reducing the weed seed bank and, as a consequence, the level of weed population and the inputs to control them. One way of reducing weed seed production is to occupy the area at all times with crops or cover crops (Almeida, 1991; Adegas, 1998). Kliewer (2003), in Paraguay, demonstrated the viability of practicing no-tillage without herbicides during successive years where the main strategy in a production system of soybean–wheat–soybean and maize–wheat–soybean was to use cover crops with fast growth and short cycle during the period between the summer crop and the wheat. Sunflower (*Helianthus annuus* L.) and sunn hemp eliminated the period of weed growth and reproduction. Therefore to reduce and eventually eliminate the use of herbicides, an appropriate rotation of ground covers and crops, a mulch effect on weed suppression, weed seed production control, and weed seed bank depletion are strategies to be pursued.

4.4 Conclusions

Cover crops can be used most reliably to suppress weeds during the vegetative growth phase of the cover crop (Table 4.1). Adapted warm-season cover crops can be used in rotations in subtropical and tropical areas to reduce populations of important weeds during fallow periods (Akobundu *et al.*, 2000; Skora Neto and Campos, 2004). Adapted cool-season cover crops can also suppress weeds during fallow years in northern temperate regions such as the semiarid Canadian Great Plains (Blackshaw *et al.*, 2001) or northern Europe (Thomsen *et al.*, 2004; Graglia *et al.*, 2006). It is noteworthy that live cover crops can be effective in suppressing important perennial weeds ranging from cogongrass in Africa to quackgrass and Canada thistle in Scandinavia. The maintenance of a vigorous ground cover during fallow periods in crop rotations represents an application of cover crops where the goals for weed management coincide well with other important environmental goals such as improving soil quality and fertility and reducing erosion.

Cover crops must be managed carefully to optimize environmental benefits and minimize potential liabilities for crop production. Cover crops that have been grown during any period unavailable for cash crops, whether a fallow period as discussed above or an off-season winter period in temperate production systems, will need to be managed before planting the next cash crop. The cover crop essentially becomes a weed that needs to be managed properly or it will become a liability rather than a benefit. These liabilities typically include consumption of soil moisture, interference with planting operations, negative effects from phytotoxins or nutrient sequestration, and direct competition with the cash crop for resources. Much of the cover-crop literature has focused on the determination of optimum management approaches for eliminating negative effects on cash crops and achieving maximum benefits.

Residue remaining after death of the cover crop is less reliable for suppressing weeds, particularly for the duration of a cash-crop season. This has led to many lines of research to enhance the inconsistent weed control achieved by cover crop residue. Attempts to increase residue biomass can enhance weed suppression but can also enhance the probability of crop suppression. Another strategy has been the use of the more effective weed-suppressive capabilities of live cover crops by developing various intercropping systems; however, research has shown that most live cover crops effective enough to suppress weeds will also suppress crops. Thus, the biggest trade-offs between optimizing weed control and enhancing environmental protection occur during the cash-cropping period that follows cover cropping. In this case, since the cover crop cannot be expected to adequately control weeds without interfering with the cash crop, management of cover crops should focus on enhancing their environmental benefits to the agroecosystem rather than their contribution to weed management.

Cover crops may ultimately contribute most to weed management within subsequent cash crops by reducing weed populations during fallow periods. The agronomic goal would be to replace unmanageable weed populations with a more manageable cover crop population. As discussed above, live cover crops can significantly suppress weed biomass, seed production, and growth of perennial structures. In addition, research has suggested that live vegetation may be important for enhancing the activity of seed predators and the reduction of seed populations. More research is needed in order to understand the effects of cover crops on weed seed production and predation and on seed mortality in soil. More research is also needed on perennial weed responses to cover crops. Regulation of weed population dynamics and community structure could become an important objective for future weed management programmes using cover crops. Research in many areas of the world has shown that the suite of management practices deployed in association with cover-cropping rotations (e.g. tillage, herbicide, mowing, and the timing of these operations) often enhance weed management more than cover crops alone. Long-term cover-cropping strategies are needed that integrate cover-crop management, weed population regulation, and enhanced environmental services.

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