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Cover crops and living mulches

Nathan L. Hartwig
Corresponding author. Department of Crop and Soil Sciences, Penn State University, 116 A.S.I. Building University Park, PA 16802; nlh@psu.edu

Hans Ulrich Ammon
Trottenstr. 34, CH-8180 Buelach, Switzerland

Cover crops and living mulches bring many benefits to crop production. Interest in winter annual cover crops such as winter rye and hairy vetch for ground cover and soil erosion control has been increasing in the last 30 yr in some areas. The integration of cover crops into a cropping system by relay cropping, overseeding, interseeding, and double cropping may serve to provide and conserve nitrogen for grain crops, reduce soil erosion, reduce weed pressure, and increase soil organic matter content (Hartwig and Hoffman 1975). Hairy vetch has increased availability of nitrogen to succeeding crops, increased soil organic matter, improved soil structure and water infiltration, decreased water runoff, reduced surface soil temperature and water evaporation, improved weed control, and increased soil productivity (Frye et al. 1988). More recent research with perennial living mulches, such as crownvetch (Hartwig 1983), flatpea, birdsfoot trefoil, and white clover (Ammon et al. 1995), has added a new dimension to the use of ground covers that eliminates the need to reseed each year. Cropping systems with the use of ground covers have been worked out for vineyards, orchards, and common agronomic crops, such as corn, small grains, and forages. Legume cover crops have the potential for fixing nitrogen, a portion of which will be available for high-nitrogen–requiring crops such as corn. In areas where excess nitrogen is already a problem, the use of ground covers may provide a sink to tie up some of this excess nitrogen and hold it until the next growing season, when a crop that can make use of it might be planted (Hooda et al. 1998). Even legumes tend to use soil nitrogen rather than fixing their own, if it is available. It is these possibilities that provide the incentive for looking at the effect of various kinds of cover crops on soil erosion, nitrogen budgets, weed control, and other pest management and environmental problems.

Nomenclature: Crownvetch, *Coronilla varia* L. 'Penngift'; birdsfoot trefoil, *Lotus corniculatus* L.; corn, *Zea mays* L.; flatpea, *Lathrus sylvestrus* L.; hairy vetch, *Vicia villosa* Roth; white clover, *Trifolium repens* L.; winter rye, *Secale cereale* L.

Key words: Catch crop, cover crop, erosion control, living mulch, nutrient management, vegetation management.

Historical Perspective

"The rise of civilization depends on the ability of a culture to produce not just enough food for survival but a surplus of food. Maintaining the productivity of the soil that feeds an ever increasing population is essential to this process" (Paine and Harrison 1993).

In the United States, abundant, cheap, fertile land did not encourage farmers to develop an awareness or interest in preserving soil productivity through soil conservation until the 1930s. In the 1920s, the U.S. Department of Agriculture recognized the problem of soil erosion. The Dust Bowl of the 1930s forced farmers and the public alike to become concerned about soil erosion and adopt conservation practices that included cover crops.

The discovery of synthetic organic herbicides in the late 1940s made reduced tillage practices more feasible because tillage was not the only method of weed control. But in the 1950s and 1960s, agricultural production increased because of increased fertilizer inputs, agricultural chemicals, and fossil fuels rather than conservation practices. This intensified production is still often associated with environmental pollution. Farmers often apply more fertilizer than required (Kleinhenz et al. 1997). Conservation practices were sometimes sacrificed to increase production. In the 1970s, concern about the environment grew and more agriculturists and environmentalists explored methods of using more natural fertilizers, such as manures and legumes. In 1973, the oil embargo drove up the prices of fuel and petroleum-based chemicals, forcing the agricultural community to investigate the use of reduced tillage and other conservation practices. Less tillage, which left more crop residue on or near the soil surface, reduced the need for fuel and reduced soil, nutrient, and pesticide runoff as well. Though dead mulches and cover crops have been in use for centuries, environmental concerns paved the way for more exploration and refinement of their use.

Cover Crops and Living Mulches

A cover crop is any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted. Living mulches are cover crops planted either before or with a main crop and maintained as a living ground cover throughout the growing season. If the living mulch is a perennial, it may be possible to main-

Table 1. Average water, soil, and cyanazine[a] runoff losses from a 14% slope planted to conventional and no-till corn (*Zea mays* L.) with and without a birdsfoot trefoil (*Lotus corniculatus* L.) or crownvetch (*Coronilla varia* L.) living mulch for three growing seasons (1977–1979) (Hall et al. 1984).

	CT[b]	NT-CSM	NT-BFT	NT-CV
Water runoff (L ha^{-1})	145,000[c]	14,900 (90)[d]	6,350 (96)	5,925 (96)
Eroded soil (t ha^{-1})	14.22	0.42 (97)	0.06 (99.6)	0.02 (99.9)
Cyanazine loss in runoff water (% of applied)	2.4	0.31 (87)	0.12 (95)	0.12 (95)
Cyanazine loss in sediment (% of applied)	0.2	0.01 (95)	0.0 (100)	0.0 (100)
Total cyanazine loss (%)	2.6	0.32 (88)	0.12 (95)	0.12 (95)

[a] Cyanazine preemergence at the rate of 2.25 kg ai ha^{-1} on CT and 4.5 kg ai ha^{-1} on NT.
[b] Abbreviations: CT, conventional tillage–rototilled; NT-CSM, no-till in corn stover mulch; NT-BFT, no-till in CSM + birdsfoot trefoil living mulch; NT-CV, no-till in CSM + crownvetch living mulch.
[c] Data collected from seeding to harvest of corn.
[d] Reduction (%) relative to the CT cropping system that received half the cyanazine rate.

tain it from year to year without the need for reseeding (Hartwig 1983, 1987). The next year's crop is planted into the suppressed cover crop usually by some no- or minimum-tillage method.

The Swiss are very interested in living mulches. Switzerland is mountainous, with precipitation of up to 1,200 mm yr^{-1} in arable regions. The conventional cropping system, using a moldboard plow or intensive mechanical cultivation, has a potential for high soil erosion, which increased when herbicides made it possible to keep the soil weed free for the whole year.

Soil erosion problems first occurred in European vineyards, in regions with high precipitation. Special types of mulch management and new living mulch systems that avoid crop yield reductions have been developed for local ecosystems, and soil erosion is no longer a problem.

With the positive results in vineyards, there was interest in using living mulches in fruit and field crops, especially corn and vegetables. The use of living mulches required new cropping techniques and new weed control strategies. Because a living mulch also influences disease and other pests, interdisciplinary research is required (Feil 2001) and weed science plays a key role.

The integration of cover crops into a cropping system by relay cropping, overseeding, interseeding, and double cropping may serve to provide and conserve nitrogen for grain crops, reduce soil erosion, reduce weed pressure, and increase soil organic matter content (Hartwig and Hoffman 1975). Before 1945, cover crops were used for these purposes and as a source of forage in integrated agricultural systems. Since 1945, the development of relatively inexpensive inorganic fertilizers and the concurrent widespread use of herbicides have caused a dramatic decline in the use of winter cover crops (Frye et al. 1985). Much of the research on cover crops has centered on the use of legumes to supply nitrogen for future grain crops (Ebelhar et al. 1984; Hargrove 1986; Mitchell and Teel 1977). But long before nitrogen was recognized as a problem in the environment, Morgan et al. (1942) documented the ability of cereal grain cover crops to reduce the leaching of nitrate and other nutrients from the root zone. Thus, the use of cover crops can address two distinctly different issues. In the case of legumes, cover crops supply organic nitrogen but also may use available soil nitrogen. Recent advances in soil testing permit the measurement of soil nitrogen with good correlation to crop growth needs that may allow us to reduce or even eliminate nitrogen applications when they are not needed (Fox et al. 1989; Griffin and Laine 1983; Magdoff et al. 1984; Ruby and Griffin 1985).

Economics of Cover Crops

The beneficial effects of legume cover crops on nonlegume crops are not just the direct effect of nitrogen fixation. LaRue and Patterson (1981) showed the value of green manures in adding nitrogen to the soil and suggested that the cost of the fertilizer saved may serve as an indication of the economic value of nitrogen fixation. Frye et al. (1985) conducted an experiment to determine if growing a legume cover crop during the winter and using no-till practices for corn production could increase profits through higher grain yields or lower production costs. They found that the combination of hairy vetch and 100 kg N ha^{-1} of fertilizer nitrogen consistently gave the highest grain yields and economic returns. When compared with corn grown in corn residue, hairy vetch resulted in additional net returns of $199, $91, and $157 for the 0, 50, and 100 kg ha^{-1} fertilizer nitrogen rates. Thus, they concluded that hairy vetch with 100 kg ha^{-1} nitrogen was potentially more economical than corn grown in corn residue with 150 kg ha^{-1} fertilizer nitrogen. Frye (1986), in a similar experiment, reported that extremely dry weather caused low corn yields across all winter cover treatments (hairy vetch, rye, and corn residue) in no-till corn and net returns were below operating costs, except at the 40 kg fertilizer nitrogen rate. But yields with legume cover treatments for a 5-yr period were sufficiently greater than those with corn stover residue, and so they more than paid for cover crop seeding costs.

Benefits of Cover Crops

Erosion Control

The primary benefit of cover crops is reduction of water runoff and soil erosion, which ultimately results in improved soil productivity. No-tillage and other conservation tillage practices combined with cover crops can significantly reduce runoff and soil erosion losses (Hartwig 1988; Langdale 1983; Langdale and Leonard 1983). Hall et al. (1984) reported that when corn was planted into a birdsfoot trefoil or crownvetch living mulch on a 14% slope, water runoff, soil loss, and pesticide loss were reduced from 95 to > 99% compared with conventional till corn (Table 1). The soil loss from corn planted into birdsfoot trefoil and crownvetch

TABLE 2. Average water, soil, and atrazine[a] runoff losses from sloping fields planted to conventional or rotary band corn (*Zea mays* L.) planted into a grass–legume sod (mean for three trials) (Rüttimann 2001).

	CT[b]	Rotary band	Reduction	LSD (0.05)
			%	
Water runoff (L ha^{-1})	118,242[c]	58,466	50	34,175
Eroded soil (t ha^{-1})	8.303	0.25	97	3.956
Atrazine loss in sediment (% of applied)	0.52	0.006	99	0.11
Atrazine loss in runoff water (% of applied)	0.79	0.265	67	0.41
Total atrazine loss (%)	1.31	0.271	79	0.31

[a] Atrazine preemergence at the rate of 1.5 kg ai ha^{-1} on whole trial.
[b] Abbreviations: CT, conventional tillage–moldboard plowed, disked, and harrowed in spring; Rotary band, corn planted into a rototilled band with atrazine-suppressed sod in between rows.
[c] Data collected from seeding to harvest of corn.

was insignificant. Soil is susceptible to erosion when there is no vegetative ground cover or plant residue on the surface. A cover crop provides vegetative cover during those periods when a crop is not present to cushion the force of falling raindrops, which otherwise would detach soil particles and increase erosion. It also slows the rate of runoff, thus improving moisture infiltration into the soil. The goal is to reduce soil erosion to something less than 4 to 5 tons ha^{-1} yr^{-1} (Renard et al. 1997). With the living mulch system, the value of soil not lost to erosion would be at least $100 ha^{-1} yr^{-1} (Pimentel et al. 1995).

In Swiss trials of rotary band seeding in a grass–legume sod cover, plant residues were incorporated in the band and the chemically suppressed sod between the bands reduced the risk of erosion to near zero (Rüttimann 2001) (Table 2).

Reduction in Surface Water Pollution

With the continuous presence of cover crops, surface water runoff is greatly reduced, and the loss of nutrients and pesticides by this route are almost totally eliminated (Hall et al. 1984; Rüttimann 2001) (Tables 1 and 2).

Added Organic Matter

Cover crops, as well as manure or crop residues, add organic matter to the soil, which increases soil tilth and productivity. At one time, soils of the U.S. corn belt contained about 12% organic matter. After 100 yr of crop production, the average organic matter content is now less than 6% (Odell et al. 1984). The average organic matter content of most agricultural soils is even lower, so any increase in organic matter will benefit these soils even more. In no-till crop production, the organic matter becomes concentrated at the soil surface, which greatly improves soil tilth.

Improved Soil Structure and Tilth

Cover crops improve soil structure, tilth, and water-holding capacity and reduce the chance of environmental pollution from nitrogen fertilizers (Danso et al. 1991). Organic matter bonds soil particles into aggregates. Also, the breakdown of plant residues by soil microbes produce gums that glue larger aggregates together into peds. This process results in greater soil permeability and aeration, which eases crop emergence and promotes root growth. Tillage is easier in a soil with good tilth and planting, even when it is easier done without prior tillage.

Fixing of Atmospheric Nitrogen

Legume cover crops fix nitrogen from the atmosphere, which can reduce the need for nitrogen fertilizer. Stem, leaf, and root residues left in the field from legumes are higher in nitrogen content than grasses. The breakdown of legume plant residues commonly releases some of this nitrogen for use by succeeding crops. Corn or small grains that require added nitrogen can benefit from nitrogen released by previous legume crops or cover crops (Ebelhar et al. 1984; Fox and Piekielek 1988; Hargrove 1986; Kroontje and Kehr 1956; Mitchell and Teel 1977). Haystead and Marriot (1978) concluded that significant nitrogen transfer occurred only when the legume crop or cover crop reached maturity or when stressed through shading or defoliation. The determining factor in total nitrogen contribution of a cover crop is the amount of dry matter produced by the cover crop (Fribourg and Johnson 1955; Holderbaum et al. 1990).

The use of annual, winter annual, or perennial legumes to provide some nitrogen early in the growing season may provide an opportunity to reduce nitrogen inputs without reducing crop yield. Holderbaum et al. (1990) showed that hairy vetch had the highest nitrogen content of all cover crops because of high dry matter yield, followed by bigflower vetch (*Vicia grandiflora* Scop.) and crimson clover (*Trifolium incarnatum* L.). Nelson (1944) found that hairy vetch and crimson clover were the most productive of five legumes evaluated for contribution of nitrogen to cotton (*Gossypium hirsutum* L.). Frye et al. (1988) reported that hairy vetch excelled in dry matter yield and nitrogen content in most studies. Ebelhar et al. (1984), Elliot et al. (1987), Hargrove (1986), and Hoyt (1987) found that hairy vetch planted in the fall and allowed to grow until crop-planting time the following spring produced aboveground dry matter yields of 5.1, 4.6, 4.2, and 3.7 Mg ha^{-1} and contained 209, 153, 158, and 130 kg ha^{-1} of nitrogen, respectively. DeGregorio and Ashley (1987) found that no-till sweet corn fertilized with less than the recommended amount of nitrogen was a darker green, taller, and leafier and had more marketable ears when planted into killed hairy vetch rather than killed winter rye. Vrabel et al. (1982) and William (1986) found that white clover provided up to 84 kg ha^{-1} to sweet corn strip-tilled into it. Bush winter squash (*Cucurbita maxima* Duch.) strip-tilled into white clover produced significantly higher yields than did squash strip-tilled into grass (Whitney and Pierce 1983). Snap beans (*Phaseolus vulgaris* L.) planted into white clover can reach full yield potential without any added nitrogen (Ashley et al. 1987). A well-established stand of crownvetch contributed up to 50 kg ha^{-1} nitrogen to first-year corn and contributed 22 to 44 kg ha^{-1} to second-year corn (Cardina and Hartwig 1981; Garibay et al. 1997; Mayer and Hartwig 1986). Mitchell and Teel (1977) compared grass and legume cover crops in no-till corn grain production. Corn yields for 2 yr with rye–hairy vetch and oats–hairy vetch mixtures were greater than those obtained with 112 kg ha^{-1} of nitrogen fertilizer both with and without irrigation. Reduced nitrogen application reduces the potential for nitrate pollution of groundwater. Although there is renewed interest in the use of legume cover crops to supply soil nitrogen, inorganic fertilizers are still the primary source of nitrogen for grain production (Hofstetter 1988).

Recycling of Unused Soil Nitrogen

From an agronomic perspective, high nitrate levels in groundwater due to leaching of nitrogen from the crop root zone represents a loss of a resource required for crop production. For corn grain production, recommended nitrogen fertilizer rates are based on utilization efficiencies of approximately 60%; however, suboptimal growing conditions can reduce this percentage to much lower levels (Chichester and Smith 1978; Stanford 1973). The relatively inefficient use of nitrogen in crop production has been recognized for some time (Allison 1955), but until the recent environmental concerns, the unused portion of applied nitrogen was largely ignored or assumed to be lost as a gas. Current environmental concerns favor emphasis on the development of strategies to reduce the need for commercial nitrogen fertilizer.

According to Pennsylvania's Nutrient Management Act, the procedures for dealing with excess manure are to sell or give it away, decrease the number of animals in the operation, or increase the amount of land on which manure is spread. These are not always feasible options for farmers. Unused end-of-season nitrogen tends to leach out of soil during the fall, winter, and spring and may end up in groundwater. Therefore, additional methods to reduce the nitrate leaching are needed.

Cover crops can reduce the chance of environmental pollution from excess nitrogen (Danso et al. 1991). One approach is to plant legume or grass cover crops that grow after the primary crop slows or stops nitrogen uptake. These cover crops need to be adapted to relatively cool fall or spring conditions to be effective. Hairy vetch lowered the potential for NO_3 leaching during spring (Corak et al. 1991). There is evidence that excess nitrogen in the soil will be used by legumes to suppress their own nitrogen fixation (Danso et al. 1991). Nitrogen applications are known to reduce nodulation and nitrogen fixation in pasture legumes, the response varying with species, cultivar, amount of nitrogen applied, time and site of nitrogen application, and prevailing environmental conditions. The application of 10 kg N ha^{-1} instead of 2 kg N ha^{-1} after each harvest decreased nitrogen fixation in white clover but not in birdsfoot trefoil (Danso et al. 1991). Uptake of excess nitrogen in soil by plants reduces the possibility of nitrate leaching and may eliminate many of the environmental problems associated with excess nitrogen in agricultural systems.

Greater Soil Productivity

If an ever-growing population is to be fed, production will have to increase. This may require farming marginal soils with already low productivity. Such soils benefit most from cover crops, but cover crop use on better soils also will reverse the downward trend in productivity as a result of losses in organic matter, nutrients, and topsoil. Living ground covers stop nutrient loss in surface runoff and tie up excess nitrate, nutrients, and residual pesticides to prevent leaching into the groundwater.

Weed Control

The presence of winter annual or living mulches will help control escape weeds and may prevent or slow down the invasion of new weeds that might otherwise become a problem in no-till corn (Hartwig 1977, 1989). DeGregorio and Ashley (1985, 1986) found that a white clover living mulch provides weed control comparable to current commercial herbicide programs in sweet corn and snap beans. In addition, winter rye, ryegrasses (*Lolium* spp.), and subterranean clover (*Trifolium subterraneum* L.) are allelopathic and help to suppress or control weeds. In a study by Else and Ilnicki (1989), subterranean clover provided nearly perfect weed control both with and without a corn crop. This suggests that some mulches can, in the presence of a corn crop, provide adequate weed control without the use of herbicides or mechanical tillage. Teasdale (1988) reported that hairy vetch residue suppressed pigweed (*Amaranthus* spp.), foxtail (*Setaria* spp.), and velvetleaf (*Abutilon theophrasti* Medikus), and he also suggested that maximum weed suppression by hairy vetch residue occurs shortly after cover crop death. The idea of using a living mulch as a "designated weed" and learning to live with it is very appealing when compared with the constant battle of learning to fight an ever-changing weed spectrum.

Evolution of Cropping Systems with a Living Mulch in Europe

Vineyards

Grapes were brought to Europe by the Romans. The Roman conqueror instructed the local growers to keep the soil weed free. Initially, weeding was done by hand, then mechanically, and, most recently, by repeated use of residual herbicides.

Because vineyards are usually on sloping land, even with hand weeding, soil erosion was a problem and Swiss farmers built stone retention basins to collect the eroded soil that was hauled back up the slopes. Mechanical weeding was never perfect, but the dislodged weeds acted as a dead mulch. When herbicides became available for use in vineyards, they provided close to perfect season-long weed control, and with preemergent herbicides, not even a dead mulch remained. As a result, there was an alarming increase in soil erosion.

After a few years, the efficacy of herbicides decreased, and the weed flora shifted to perennials such as bindweed (*Convolvulus* spp.) and herbicide-resistant weed biotypes that resulted in a green ground cover again. Because of the high cost of labor, hand weeding was no longer an option. Common chickweed (*Stellaria media* L.) also was one of the widespread uncontrolled weeds. To the astonishment of vine growers, grape yields remained the same despite the weeds, and obviously in the weedy areas soil erosion was reduced. Using specially selected herbicides that favored the development of common chickweed, Stalder et al. (1977) proposed that the weed be used as a living mulch. This idea never caught on because seeding weeds was unacceptable to most growers. Growers preferred mustards (*Brassica* sp.), which were easier to manage. Suppression proved to be necessary in dry regions to avoid competition for water.

The aversion of farmers to any living vegetation in vineyards and the fear of loss of wine quality, problems with diseases and pests, and other environmental effects provided the impetus for a range of trials to test the (assumed negative) influence of living green ground covers. According to trial results for 10 to 20 yr and field experiments on several thousands of hectares in many European countries, the following conclusions were reached—(1) Loss of wine quality was not a problem when the mulch species and the duration of living mulch were adapted to the local climate. (2) Water competition can be avoided by limiting the duration of living mulch from season-long in moist regions to a few months in dry regions or by maintaining the living mulch only between the rows (Gut 2002; Gut et al. 1996). (3) Nutrient competition seems to be no problem because European vineyards are well fertilized and vines are deep rooted. But reduction of nitrate in the soil can reduce bunch stem necrosis up to 50% (Boller et al. 1997). (4) Soil erosion and fertilizer loss in water are nearly eliminated in a living mulch when compared with winter ground cover, part-time or part-surface living mulch, or part-time dead mulch. (5) Entomaphageous (beneficial) insects increased more than other pest species (Remund et al. 1992). *Trichogramma* parasitism on European grape berry moth (*Eupoecilia ambiguella*) increased from 64 to 85%, and *E. ambiguella*–infested grapes were reduced from > 15 to < 2% when grown with a living mulch (Boller et al. 1997). (6) Weed control is easier because hard to control species such as bindweeds suffer from increased competition and many triazine-resistant biotypes, such as pigweeds, (*Amaranthus* spp.), manyseeded goosefoot (*Chenopodium polyspermum* L.), common groundsel (*Senecio vulgaris* L.), and horseweed [*Erigeron* (*Conyza*) *canadensis* L. Cronq] (Beuret 1984), are no longer a problem. In fact, some environmentalists claim that the traditional vineyard weeds weinberg tulpe (*Tulipa sylvestris* L.) and bisamhyazinthe (*Muscari racemosum* L.) have disappeared (D. Gut, personal communication). Plant species diversity was found to be higher, especially in the case of permanent cover (Gut et al. 1996).

Fruit Production

With the positive results in vineyards, trials with living mulches in fruit production also have intensified. Today, use of a living mulch is a common practice in apple (*Malus sylvestris* L.) production. Here, the permanent cover is between the rows, with a bare strip over the tree row (Gut 2002; Gut et al. 1997). The advantages are easier weed control and better nitrate management.

Vegetables

Trials with a living mulch are reported with underseeding in cabbage (*Brassica oleracea* L.) (Bellinder et al. 1996), leek (*Allium ampeloprasum* L.) (Baumann and Imhof 1996), and potatoes (*Solanum tuberosum* L.) (Rajalahti and Bellinder 1996). Baumann and Imhof (1996) reported a reduction from 100% attack by thrips (*Thrips tabaci*) in leek to 42 and 63% at the first and third week after leek planting, respectively, when interseeded with legumes. As the management of the interseeded plants proved to be difficult, the system was not acceptable to farmers.

Arable Crops

Traditionally, the main arable crops in Europe were fall-seeded small grains. With these crops the soil was covered during the period of erosive rains in winter and spring. With the increase of corn from 4,000 ha in 1960 to 600,000 ha in 2000 in Europe (66,000 ha in Switzerland), the erosion potential during the growing season has been greatly increased. The greatest danger is from heavy spring thunderstorms before the corn provides sufficient ground cover. The experience of planting corn into a chemically killed sod was not satisfactory because the dead mulch protected the soil only for a short period after seeding and by harvest the decayed mulch did not provide cover for the following fall, winter, and spring.

Living Mulch in Corn

The first attempts to introduce green soil cover were by underseeding corn with clover (*Trifolium* spp.). The seeding was combined with mechanical cultivation at about the three-leaf stage of corn. With this timing, corn yields were not reduced and some green cover remained at harvest, reducing soil compaction and providing soil protection during the fall and winter. But reduction of soil erosion in corn failed because clover establishment was too slow.

No-till Seeding

No-till cover crop seeding techniques used in the United States were tried, e.g., seeding winter rye or hairy vetch in the fall and killing this cover crop with herbicides in spring. Instead of killing the cover crop, Swiss farmers used the forage as hay or pasture before corn planting. No-till corn planting is now a common practice in some areas of Switzerland.

Band Seeding in Living Mulch

Ammon et al. (1995) introduced rotary band seeding that leaves a living mulch between rotovated strips. A grass–clover mixture was seeded as a forage or pasture crop before corn and could be harvested as silage before corn planting, when rotating to no-till corn. A four-row band tiller–seeder included four band rotovators working a 15-cm-deep, 30-cm-wide strip with a winged tine 30 cm wide working about 20 cm deep preceding the rotovator. A band fertilizer applicator incorporated the fertilizer in the rotovated band, and two band sprayers applied different herbicides on the rotovated bands and between the bands independently. Normally, about 30 kg of nitrate ha^{-1} was incorporated into the band to compensate for nitrogen retention by decomposing plant material. Between the rotovated strips, the forage species were kept as a living mulch as long as possible or suppressed either mechanically or with herbicides when necessary to avoid water or nitrate competition. After a series of trials, beginning in 1988 until 2000, the following conclusions were drawn: (1) water and nitrogen are the main competition factors, but both can be avoided by timely suppression of the green cover between the bands; (2) in moist regions with > 1,100 mm precipitation, green mulch can be kept season-long, and mechanical mulching or cutting between the rows is sufficient for the prevention of water competition; and (3) in regions with less precipitation, a suppression of the green mulch with herbicides is needed; the aim is not to kill the vegetation completely but to diminish the competition during the critical period of corn growth early in the season.

A grass–clover mixture as a living mulch can be treated with 1 kg glyphosate ha^{-1} applied preemergence to the corn crop. This kills most grasses that remain as dead mulch and suppresses the regrowth of clover that recovers after a few weeks as a green mulch. Glyphosate-resistant corn cultivars now allow application timing for good weed control without concern for crop injury (Ammon and Scherrer 1996). Postemergence rimsulfuron can be used, but there is some risk of phytotoxicity to the corn and cover crop suppression is not as good.

A pure clover stand can be managed with glufosinate. The *Poa* species or other grasses normally present in clover will only be damaged and regrow later as a green mulch. In conventional cultivars, the spraying needs to be done preemergence. In glufosinate-resistant cultivars, the spraying can be delayed as long as possible to prevent new weeds from emerging, but early enough to make the nitrogen in the mulch available to the corn crop. Accurate timing of herbicide application is required to avoid crop losses.

Nitrate competition is mainly dependent on the species selected as a living mulch. Crop yields were higher in all trials, when legumes instead of grass species were used as a living mulch. With additional nitrate fertilization, part of the yield loss due to grasses could be alleviated (Garibay et al. 1997). Positive effects of legumes in similar cropping systems have been reported with alfalfa (*Medicago sativa* L.) (Eberlein et al. 1992), crownvetch (Hall and Hartwig 1990; Hartwig 1983), hairy vetch (Teasdale 1993), subterranean clover (Enache and Ilnicki 1990), and white clover (Fischer 1988; Garibay et al. 1997; Vrabel et al. 1982; William 1986).

Living Mulch Systems Trial in Switzerland

Cropping Systems

The influences of cropping systems were tested in a 4-yr (1990–1993) interdisciplinary trial in cooperation which entomologists, pathologists, nematologists, and soil and weed scientists. The following four cropping systems were used: (1) T = traditional—moldboard plow in autumn, seedbed preparation in spring, broadcast preemergence or early postemergence herbicides (atrazine + metolachlor); (2) US = underseeded—seedbed preparation as in traditional, herbicides (same as in T) applied in drill bands of 30-cm width, cultivated twice for weed control followed by underseeding a grass–clover mixture (*Lolium perenne* and white clover), 370 g ha^{-1} when corn was 20 to 40 cm tall; (3) GR = green manure rye—rye seeded in autumn after main corn crop (plow or chisel plow), flail chopping of rye in spring before planting corn with rotary band seeder (in Band Seeding in Living Mulch) in the living rye stubble, herbicides (same as in T) in drill bands of 30-cm width, rye regrowth (living mulch) between corn rows vertically mulched once with a specially constructed, tractor-mounted multiple-row mulcher; and (4) CM = corn meadow—a grass–white clover meadow, harvested as silage for cattle feed in spring before corn planting, corn planted with rotary band seeder in the living stubble, herbicides (same as in T) in drill bands of 30-cm width, grass–white clover regrowth (living mulch) between corn rows vertically mulched twice.

In a series of additional field tests a modification of CM was used (Ammon et al. 1995) (5) CMR = corn meadow regulated with herbicides. The system was as in CM, but instead of the mechanical mulching, herbicides were used to suppress but not completely kill the grass–white clover regrowth between the corn rows. Timing and choice of the herbicides were chosen in accordance with the local climate and the plant species used as a living mulch. This system is advised in regions with precipitation below 1,100 mm yr^{-1}.

Influence of Cropping Systems on Soil Organisms

Earthworm

Earthworm biomass in any green soil cover increased. Worm biomass was about seven times higher in CM than in T, possibly because of the combination of living mulch and no-till cropping technique.

Collembola

Collembola were significantly higher in CM when compared with the other three cropping systems. The permanent living mulch of CM offers the optimal conditions for build up of high populations. The high root production of ryegrass might have favored soil-inhabiting collemboles, but the trapping technique used was not suitable for catching soil-inhabiting collemboles.

Microbial Soil Biomass

Microbial soil biomass for GR and CM was significantly greater than that for T in 1991 and 1993 (Figure 1) (Jaggi et al. 1995). The US cropping system was never significantly different from T. The high root production of rye and the grass–clover meadow are the main factors influencing microbial activity. Other soil microbiological parameters like soil respiration, N-mineralization, and cellulose decomposition showed no difference in the four cropping systems with the testing methods used.

Influence of Cropping Systems on Diseases and Pests

Common Smut

Common smut (*Ustilago maydis*) is a fungal disease known to use mechanically injured plant surfaces for infection. Therefore, mechanical hoeing and mulching in the systems with living mulch were suspected to result in a high-

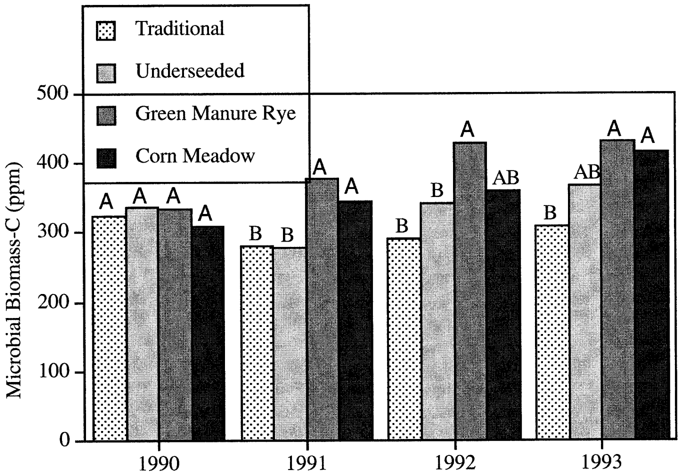

FIGURE 1. Changes in microbial biomass during 4 yr in different cropping techniques (Jäggi et al. 1995). Values with the same letter within years are not significantly different (Duncan's test, P = 0.05).

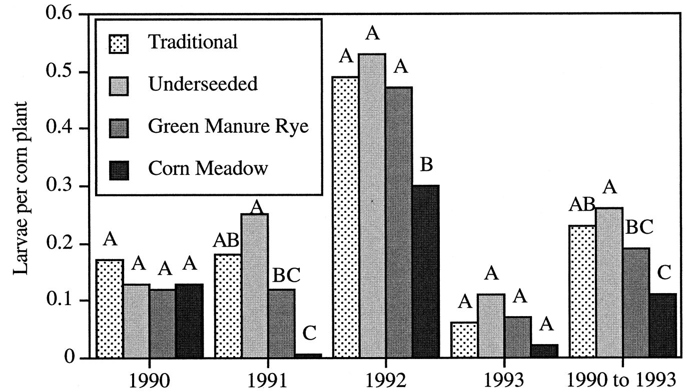

FIGURE 3. Number of European corn borer (*Ostrinia nubilalis*) per corn (*Zea mays*) plant in autumn (Bigler et al. 1995a). Values with the same letter within years are not significantly different (Duncan's test, P = 0.05)

er disease incidence. Figure 2 shows the opposite: permanent green cover in CM and rye stubble in GR resulted in the lowest disease incidence, whereas T and US with no green cover during the early-corn stage had the highest fungal infestation when averaged over 4 yr (Bigler et al. 1995a). Fungal spores that overwinter in soil have to be lifted to the corn leaves either by wind or the splash of raindrops. The dense mulch, either living or dead, acts as a filter and prevents splashing, so spores do not reach the corn leaves.

European Corn Borer

European corn borer (*Ostrinia nubilalis*) overwinters in corn stubble. Farmers are advised to carefully plow under corn stubble in winter to destroy this insect. The no-till CM and GR were suspected to promote corn borer. The 4-yr mean results in Figure 3 show that the insect attack was lowest in CM, highest in T and US, and medium in GR. Besides the relatively small experimental plots, a survey in 20 farmer fields near Zürich, 10 T and 10 CM, showed the same result: in CM, the corn borer population was 63% lower when compared with T. In another region (Swiss Rhine Valley), similar results were obtained from surveys of farmer fields: corn borer attacked 24% of corn plants in T weed-free corn, 15% in US, and 7% in no-till CM. There is higher mortality of corn borer larvae in the mulch systems with green or dead soil cover during fall, winter, and spring. The unexpected result also is explained by a higher incidence of natural enemies (see below) in living mulch systems.

Aphid

Aphid (*Aphis fabae*) density was clearly negatively correlated with green soil cover as shown in Figure 4 (Bigler et al. 1995a). During corn seedling development in the CM plots, a higher immigration rate of winged ants was observed. In a living mulch more predators are present, thereby limiting aphid populations.

Fritfly

Fritfly (*Oscinella frit*) is known to overwinter in living plants, preferably in rye. Therefore, in the rye system (GR), a greater infestation was expected. In the 4 yr of the trial, the population was generally low with a higher attack (34%) in the rye plots when compared with the other systems where about 20% attack was observed. From other observations, especially in warmer climates in the southern part of Switzerland, it is known that infestations can be very high when corn is seeded no-till in rye stubble. Larvae of the fritfly are killed if rye is mulched early in the season. In

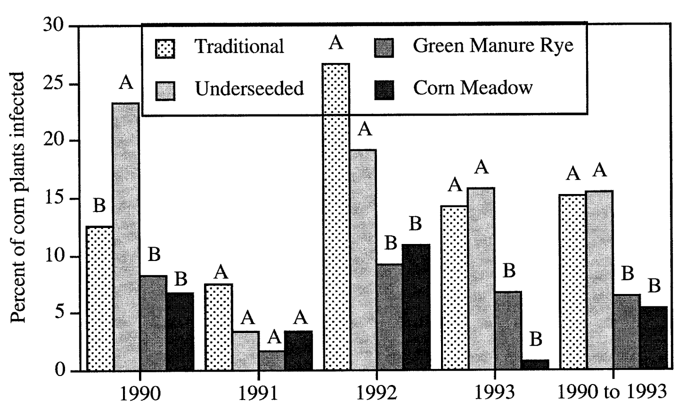

FIGURE 2. Percentage of corn (*Zea mays*) plants infested with common smut (*Ustilago maydis*) (Bigler et al. 1995a). Values with the same letter within years are not significantly different (Duncan's test, P = 0.05).

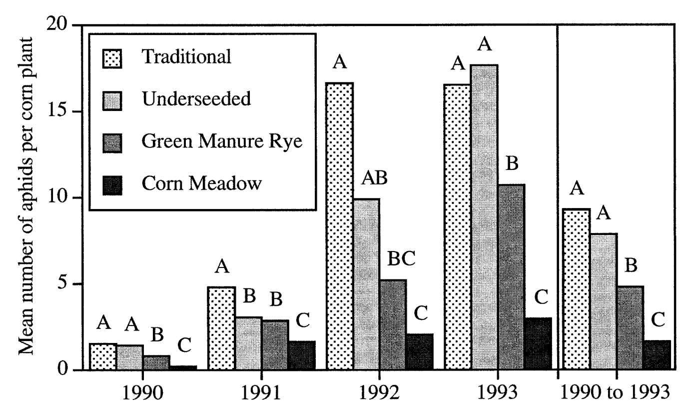

FIGURE 4. Number of aphids (*Aphis fabae*) per corn (*Zea mays*) plant (counted once per month from June to September) (Bigler et al. 1995a). Values with the same letter within years are not significantly different (Duncan's test, P = 0.05).

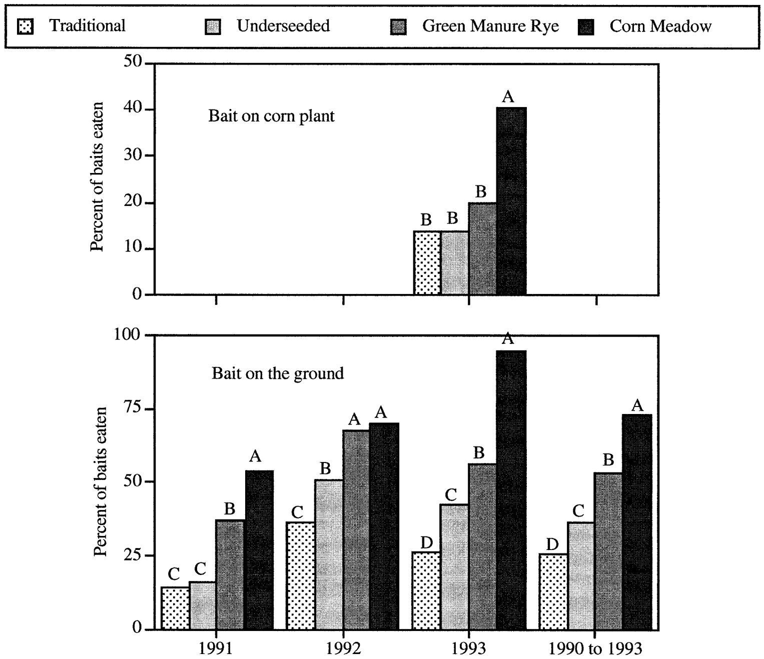

FIGURE 5. Percent bait (Corn borer [*Ostrinia nubilalis*] larvae and pupae of flour moth [*Ephestia kehmiella*]) eaten when placed on corn plants or placed on the ground during the growing season (Bigler et al. 1995b). Values with the same letter within years are not significantly different (Duncan's test, P = 0.05).

warmer climates, however, fritfly is already in the pupae stage and located in the stubble base, close to the ground, where they are not destroyed by mulching. When the adults of the fritfly emerge, corn is already in the seedling stage and hence very sensitive to fritfly attack.

Influence of Cropping Systems on Natural Enemies (Insects and Spiders)

Ground Beetle

Ground beetle (*Carabidae*) numbers caught in pitfall traps (barber traps) were highest in the rye system (GR) and lowest in T. There were 32 species found but without clear differences between the cropping systems. Rove beetle (*Staphylinideae*) numbers caught were up to three times higher in CM compared with T; GR and US were in between. The number of spiders (*Aranea*) and ants (*Formicidae*) caught in the pitfall traps was more than twice as high in CM when compared with the other systems. Green lacewings (*Chrysopidae*) and minute rirate bugs (*Anthocoriadae*) are not related to any of the cropping systems. In contrast, ladybird beetles (*Coccinellidae*) and hover flies (*Syrphidae*) followed the densities of aphids on corn plants, i.e., highest in T and lowest in CM.

Influence of Cropping Systems on Predation of Pest Insects

The different densities of several pest species like aphids and European corn borer can be explained by the higher incidence of predators. Predation increases with decreasing tillage and with increasing green cover, and to a lesser degree, with increasing dead cover on the soil (Figure 5) (Bigler et al. 1995b). In three different years, ratings were made once per month in June, July, and August. Thirty individuals, each of corn borer larvae and pupae of the Mediterranean flour moth (*Ephestia kehmiella*), were exposed three different times for 24 h on the soil as bait. In 1993, 20 larvae and 20 pupae per plot were fixed to the corn plants. The baits were protected with a coarse iron mesh from big predators like mice and birds. We concluded that the disappearance of the baits after 24 h was caused by insect predators, mainly ants and ground beetles.

Influence of Cropping Systems on Weed Development, Weed Control, and Vegetation Management

The cropping system clearly influences weedy vegetation. In T, the soil was to be kept weed free, but high survival of panicoid grasses and some triazine-resistant common lambsquarters dictated a change in the herbicide program after the first year (Figure 6) (Ammon and Sherrer 1995). Instead of atrazine only, metolachlor and spot treatments of dicamba were added. In the first years of GR, panicoid grasses and manyseeded goosefoot were common, diminishing in the following years as a result of cover crop competition. In US cropping system, the development of weeds is correlated with the seeding time; the earlier 1993 seeding was more competitive. In CM, most of the traditional species of the "maize weed flora" disappeared after the first year, which demonstrates that changing the cropping system alters the weed flora and can reduce selection for herbicide-resistant cultivars.

Weed control in a living mulch is in fact vegetation management. The living mulch needs to be suppressed, normally with herbicides that also will control weeds present in the living mulch and, if persistent, those emerging later. Therefore, herbicides used in living mulch systems need to be chosen not only for their effectiveness in controlling weeds but also their effects on the living mulch.

Weeds as an Alternative Living Mulch

Instead of seeded species used as ground cover, naturally occurring weeds can be used. Weeds in sugar beet (*Beta*

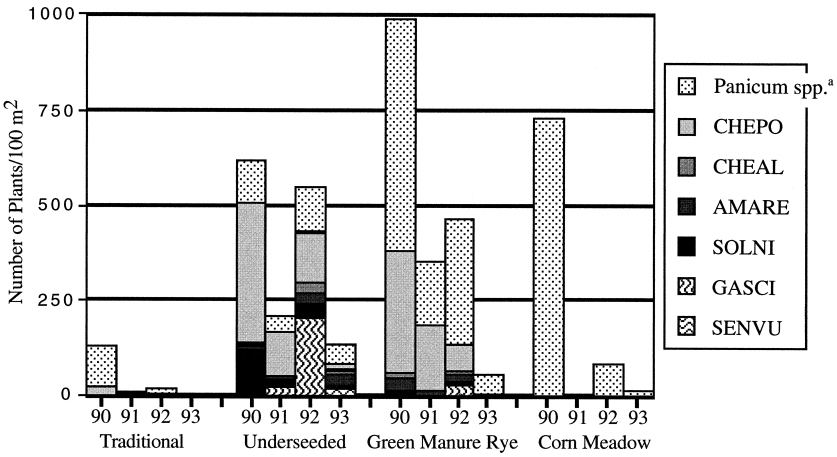

FIGURE 6. Shift of selected corn (*Zea mays*) weeds in different cropping systems in 4 yr (Ammon and Scherrer 1995). [a]Weed identification: *Panicum* spp.; manyseeded goosefoot, *Chenopodium polyspermum* L. CHEPO; common lambsquarters, *Chenopodium album* L. CHEAL; redroot pigweed, *Amaranthus retroflexus* L. AMARE; black nightshade, *Solanum nigrum* L. SOLNI; hairy galinsoga, *Galinsoga ciliata* (Raf.) Blake GASCI; common groundsel, *Senecio vulgaris* L. SENVU.

vulgaris L. ssp. *vulgaris* 'altissima' DOELL.) are normally controlled by preemergence or several postemergence herbicide mixtures. The result is a shift in the weed flora and increase in resistant weeds. Sugar beet needs to be weed free from 6 to 8 leaves until harvest and not in all seasons. (Wellmann and Märlander 1996). The main impediment to the introduction of late weed control by beet growers is the fact that, so far, all selective broad spectrum herbicides are effective only at the weed seedling stage. For late weed control, glufosinate or glyphosate in genetically modified (GM)-resistant beet offers new possibilities. When applied late, one or at most two applications of glufosinate allow sufficient weed control until beet harvest (Ammon 1996; Schäufele and Harms 1998). According to Madsen and Jensen (1995), one application of glyphosate at the eight-leaf stage provided effective season-long weed control. Late weed control in beet-restricted diseases, e.g., the development of yellow beet virus due to higher incidence of predators and lower aphid attack (Bosch 1987; Dubois et al. 1993; El Titi 1986; Häni et al. 1990). Also, any green cover or dead weed mulch after the late control reduces soil erosion.

Summary and Conclusions

Traditionally, crops are seeded in bare soil, enabling weeds to germinate without competition. Then, weeds are controlled as early and as totally as possible with all the disadvantages of soil erosion, nutrient and pesticide runoff loss, silting of streams and rivers, etc. A system based on green ground cover, either permanent (living mulch) or present during the establishment of the crop as a dead or dying mulch, has positive environmental aspects, suppresses weeds, favors predators, and can reduce disease and insect problems. The cover crop may serve as a nutrient (especially nitrate) catch crop, storing nutrients in plant biomass for the following crop. The new main crop is seeded minimum- or no-till. The cover crop may be kept green as a living mulch throughout the growing season and possibly from 1 yr to the next if it is a perennial. Before the living mulch competes with the crop, timely suppression is necessary. Therefore, highly selective pre- or postemergence herbicides are needed to manage the cover crop and the weed flora without harming the crop. The weed flora includes species different from conventional tillage. Cropping systems with a living mulch not only suppress certain weeds but also result in a change in the weed flora, which may reduce or prevent the selection for herbicide-resistant weeds. The living mulch technique is well developed for perennial crops such as vineyards and orchards. Positive results have been achieved in corn, sugar beet, and some vegetables. Problems of vegetation management and implementation of the technique in other crops remain.

Another approach is to use naturally emerging weeds as a cover crop and control these with late-postemergence herbicides. Most postemergence herbicides are not effective on all weeds or selective enough for late application, but glufosinate or glyphosate in GM-resistant crops are effective and make late posttreatments possible. For the first time in the history of chemical weed control, it is possible to choose herbicides according to their efficacy on the major weed problems for postemergence weed control in GM crops. To breed specially selected herbicide-resistant crops for use in living mulch systems is a challenge but may be possible.

A disadvantage of using a living mulch is its competition for moisture and nutrients (Echtenkamp and Moomaw 1989). Competition for moisture is minimal for perennial crops such as vineyards and orchards in areas with over 1,100 mm average annual rainfall or when the living mulch is suppressed 80 to 90% early in the growing season in areas of lesser rainfall. It also appears that corn yields are not reduced as a result of drought of 2 to 3 wk or less after corn has a good root system that can tap subsoil moisture (N.L.H., personal observation). Nutrient competition is not a problem when legumes are used as a cover crop, and competition for nitrogen when grasses are used as a cover can at least partially be overcome with additional nitrogen.

Future Prospects

The Ultimate Living Mulch

A good cropping system would have a living mulch to control water runoff and soil erosion, which produces an allelochemical to control weed seed germination and possi-

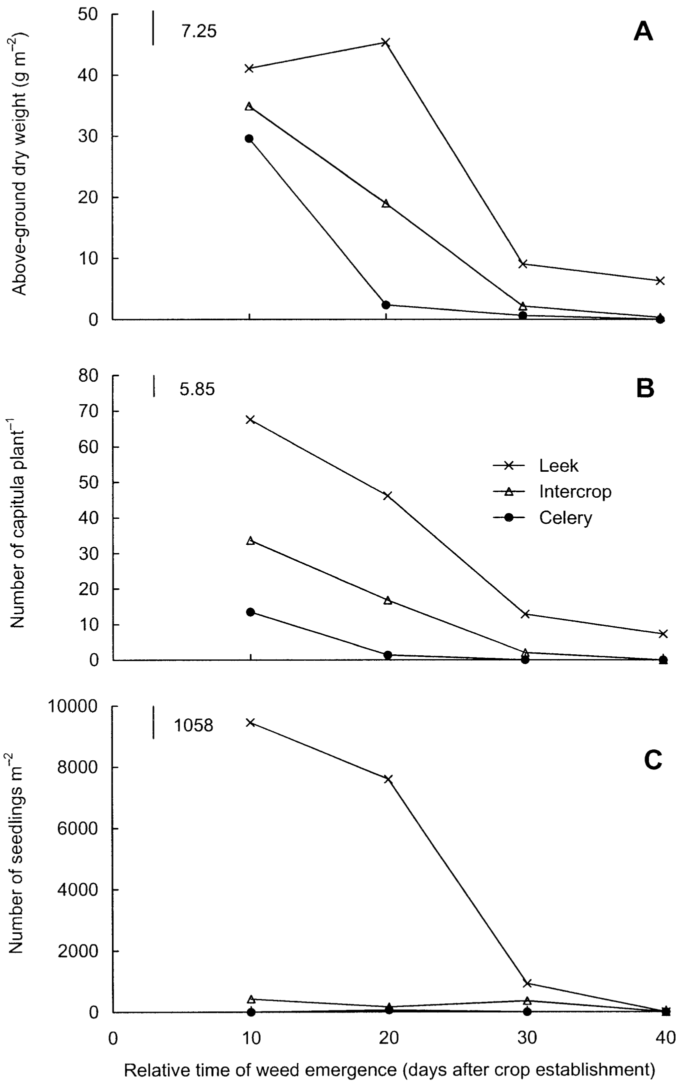

FIGURE 7. Biomass of common groundsel (*Senecio vulgaris*) at different times of weed emergence for leek (*Allium ampeloprasum* L.) pure stand (×), celery pure stand (●), and leek–celery intercrop (◊) (Baumann et al. 2000).

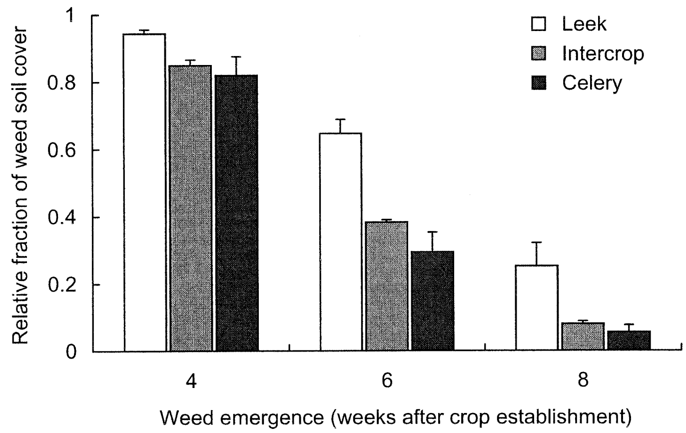

FIGURE 8. Soil cover by weeds as a function of weed emergence in leek (*Allium ampeloprasum* L.) pure stand, celery pure stand, and leek–celery intercrop (Baumann et al. 2000).

bly suppress established weeds without affecting growth and yield of the primary crop. The living mulch would have to be noncompetitive or be easily suppressed to render it noncompetitive without losing its allelopathic characteristics. This might be accomplished by gene transfer from an organism known to have allelopathic characteristics such as subterranean clover into a compatible living mulch. This would likely be more effective and acceptable by the general public than inserting the weed-controlling gene directly into the crop itself. Even an allelopathically enhanced crop such as corn would not provide good weed control between the corn rows early in the season because the rows are too far apart. Because it is no more likely that a single cover crop will be compatible with all crops than a single herbicide is safe on all crops, it will be necessary to continue the search for compatible cover crops or those that can be managed to make them compatible for each crop.

Intercropping Instead of Living Mulch?

In the living mulch system, the main risk is competition with the primary crop by the companion living mulch plants. In intercropping or mixed cropping, two or more harvestable crops are grown simultaneously on the same area of land (Willey 1979). There is competition between two harvestable species, but there is still the possibility of a greater total yield than would be obtained from either one alone. Of course, a main advantage of intercropping is weed suppression, but suppression alone is not enough, and some additional control measures are needed. In developing countries, this is solved by hand weeding. Selective herbicides are not always available for both crops as most crops suitable for intercropping are often from different plant families.

Mixed cropping is common practice in many tropical regions. In Kenya, for example, small holder farms grow 80% of potatoes, 90% of local corn, and 80% of beans under mixed cropping with positive results for weed control and total yield (Maina et al. 1996).

In India, mixed cropping of wheat and soybean (seeded 2/3 and 1/3) or wheat and mustard (seeded in equal quantities) resulted in at least 25% higher yield per unit area (Kundu 1994).

Intercropping is not used in European field crops. Thus far, in Europe, there are few successful scientific results available. In England, Clements and Donaldson (1997) and, in Scandinavia, Breland (1996) showed that intercropping of cereals with clover or cereals with Faba bean (*Vicia faba* L) (Bulson et al. 1997) is possible, but almost no on-farm research has been done. In vegetables, Baumann et al. (2000) successfully intercropped leek and celery. Leek is a weak competitor and celery a relatively good one. Grown together, e.g., one leek row and one celery row resulted in greater weed competition than the mean of both crops cultivated alone. Total weed green matter is lower (Figure 7) and especially the late-emerging weeds that need additional weed control measures are suppressed (Figure 8), and the total yield of both crops was higher than when these were cultivated separately. Because the planting and harvesting time of these crops coincides and both are harvested row by row, the system is applicable and accepted at the farm level.

In the United States, there are positive experimental results (Liebmann 1986), which prove the weed-suppressing ability of intercropping systems, but the systems are not used in farming. Most farmers and even scientists argue against intercropping systems because of difficulties of seeding two different seeds or the impossibility of harvesting two different crops mechanically. But the problems of seeding and harvesting two crops can be solved. This requires the choice of suitable crops that can be harvested at the same time and the experience to manage the system for local conditions.

In intercropping experience, developed countries seem to be underdeveloped. The ecological advantages, higher soil protection, easier pest management (Theunissen 1994), and lower herbicide needs are similar to the living mulch systems, and the risk of crop competition and yield suppression is avoided.

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