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# Living Mulch as a Tool to Control Weeds in Agroecosystems: A Review

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## 1. Introduction

Weeds are a serious constraint to increased production in crops due to reduced yield and economic returns. Weed problems are particularly problematic in row crops as a result of widely spaced crop rows. Weed control in most agroecosystems is highly dependent on conventional cultivation and herbicide applications. Conventional interrow cultivation represents an additional cost for the producer due to the consumption of fossil fuels (Lybecker et al. 1988) and is also associated with increased soil erosion as soil particles are more susceptible to displacement after tillage (Dabney et al. 1993; Fuller et al. 1995). Moreover, ground and surface water pollution by pesticides are causes for concern (Hallberg 1989), and herbicides used in crops have been among the pesticides most frequently detected in these waters (National Research Council 1989). Improving water quality and decreasing herbicide carry over is one of the more important environmental issues for farmers and agriculture researchers (Stoller et al. 1993). Herbicide-resistant weed ecotypes are being discovered more frequently, due to increased herbicide applications and subsequent selection, is also posing a serious threat to agricultural production (Holt and LeBaron 1990).

Increased interest in sustainable agricultural systems has led to significant developments in cropping practices over the past decade (Thiessen-Martenes et al., 2001). Interest in alternative and sustainable agricultural production systems that require fewer production inputs is growing (Calkins and Swanson 1995). The current emphasis on reduced pesticide use has led to increased interest in alternative weed management methods (Bellinder et al. 1994). In sustainable agriculture, an alternative method to chemical and mechanical weed control in crops is the use of living mulches. Living mulches are cover crops that are planted between the rows of a main crop such as corn (*Zea mays* L.), soybean (*Glycine max* L.), etc., and are maintained as a living ground cover during the growing season of the main crop. Although living mulches are sometimes referred to as cover crops, they grow at least part of the time simultaneously with the crop.

In addition to providing adequate cover to reduce soil erosion (Wall et al. 1991) and increase soil water infiltration (Bruce et al. 1992), legume living mulches improve soil nutrient status through addition of organic nitrogen (N) (Holderbaum et al. 1990; Brown et al., 1993) via fixed atmospheric nitrogen which improves soil physical properties (McVay et al. 1989; Latif et al. 1992). Incorporating legume living mulches can also increase the yield of the succeeding crop (Bollero and Bullock 1994; Decker et al. 1994). Leguminous living mulches have the potential to reduce dependence on fossil fuels and reduce negative environmental effects of crop production systems. Some functions these living mulches can perform are (1) fixing atmospheric N that is made available to main crop, (2) protecting soil from erosion during the main crop growing season, (3) improving soil quality, (4) reducing evaporation and increasing infiltration during the main crop growing season and (5) suppressing weeds (SAN, 1998). Improvement of soil organic matter and production of forage for animal feed are other potential uses of living mulches.

## 2. Necessity to develop alternative weed control methods in agroecosystems

Weeds are one of the major problems in crop production around the world, and we are trending toward controlling these weeds with herbicides, which comes with an increased environmental impact. At present, in most agroecosystems, weed control highly depends on chemical and mechanical practices that are very expensive, hazardous for the environment and, consequently, unsustainable. For example, currently about 95 % of the soybean acreage in the state of Minnesota in the United States (U.S.) is treated with herbicides with about 6 million kg of herbicides applied annually (Minnesota Agricultural Statistics 2001). Herbicide costs account for 35% of the variable cost of production. Overall, in the U. S. alone, 75% of crop production is based on herbicide input (Duke 1999).

However, herbicide-based control has failed to achieve long-term weed seedbank management (Mortensen et al. 2000; Weber and Gut 2005). Even with herbicides, weeds remain prominent in croplands and producers still lose considerable crop yield due to weeds (Bridges 1994). Furthermore, herbicide resistance is forcing producers to use more expensive management tactics, thereby increasing production costs. Public concern over safety has also caused a reassessment of toxicological and environmental impacts of synthetic herbicides. Therefore, because synthetic herbicides represent a significant expense and environmental concern and cannot be used by those wishing to be certified as organic producers, many producers seek alternative weed control strategies.

## 3. Benefits of living mulch systems

Living mulches have the potential to form an important component in agroecosystems and can be a useful tool for weed suppression in sustainable agricultural systems (Teasdale 1996; Bond and Grundy 2001; Kruidhof et al. 2008) including many useful advantages such as: improvement of soil structure (Harris et al., 1966), regulation of soil water content (Hoyt and Hargrove 1986), enhancement of soil organic matter, carbon dynamics and microbiological function (Steenwerth and Belina 2008), reducing soil erosion (Malik et al., 2000), soil enrichment by nitrogen fixation (Sainju et al. 2001), insectarium for many beneficial arthropod species (Grafton-Cardwell et al. 1999), and enhancement of populations of soil macrofauna (Blanchart et al. 2006). Living mulches also have the potential to suppress weed growth (De Haan et al. 1994), increase soil water infiltration (Bruce et al. 1992), decrease soil erosion (Cripps and Bates 1993), contribute N to the main crop (Corak et al. 1991) and reduce economic risk (Hanson et al. 1993).

The symbiotic relationship of legume living mulches with rhizobia bacteria allows them to use N from the atmosphere. Of major interest is whether some of the fixed N will be available to a cereal grown simultaneously with the legume. If this is the case, living mulches of legumes could reduce the need for fertilizer N. The primary mechanism of N transfer from a legume to a nonlegume is decomposition of leaves, roots, and stems of the legume (Fujita et al. 1992). However, observations in cereal–legume intercrops have confirmed that N is also excreted from legume roots and leached from leaves, thus becoming available to the cereal immediately (Fujita et al. 1992).

More efficient use of environmental resources is another important benefit of a living mulch system. For example, a legume such as crownvetch (*Coronilla varia* L.) with different root architecture than corn might absorb relatively immobile potassium (K) from deep zones in the soil that would not be accessed by corn (Vandermeer, 1990). Corn requires less soil nutrients (Richie et al. 1993) and light as it matures late in the growing season. In the presence of kura clover (*Trifolium ambiguum* M. Bieb.) as a living mulch, nutrients and light penetrating through the maturing corn canopy may be utilized by the living mulch rather than fostering weed growth (Zemenchik et al. 2000).

### 3.1 Weed suppression

Living mulches are crops grown simultaneously with the main crop that can suppress weed growth significantly without reducing main crop yield through an ability to grow fast or because they are planted at a high density (De Haan et al., 1994). Living mulches can suppress weed growth by competing for light (Teasdale 1993), water and nutrients (Mayer and Hartwig 1986), and through the production of allelopathic compounds (White et al. 1989) which may ultimately result in reduced herbicide applications. Many studies have confirmed the weed suppressing ability of living mulches in different cropping systems.

There is wide agreement in the literature that a vigorous living mulch will suppress weeds growing at the same time as the living mulch (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). In one study (Echtenkamp and Moomaw 1989), chewing fescue or red fescue *(Festuca rubra* L.*)* and ladino clover *(Trifolium repens* L.*)* were effective living mulches for controlling weed growth. Reductions in weed infestations have been reported with sunn hemp (*Crotalaria juncea* L.) as a living mulch in citrus and avocado (*Persea americana* Mill.) (Linares et al. 2008; Severino and Christoffoleti 2004). According to Mohammadi (2010) weed dry weight was reduced by 34 and 50.9% when hairy vetch (*Vicia villosa* Roth) was interseeded in corn at 25 and 50 kg $ha^{-1}$, respectively.

Moynihan et al. (1996) also reported a 65% reduction in fall weed biomass compared with non-living mulch control following a grain barley (*Hordeum vulgare* L.) and medic (*Medicago* sp.) intercrop. Velvetbean (*Mucuna pruriens* L.) suppressed the radical growth of the local weeds alegria (*Amaranthus hypochondriacus* L.) by 66% and barnyardgrass (*Echinochloa crus-galli* L.) by 26.5% (Caamal-Maldonado et al. 2001). In another research, a subterranean clover (*Trifolium subterraneum* L.) living mulch reduced weed biomass and increased soybean yield by 91 % relative to weedy control plots (Ilnicki and Enache 1992). The list of weed suppression intensity by different living mulch species are shown in Table 1.

| Living mulch species | Percentage weed suppression* | Reference |
|---|---|---|
| Red clover, hairy vetch | 75 | Palada et al. (1982) |
| Subterranean clover | 53-94 | Enache and Ilnicki (1990) |
| Hairy vetch | 70-90 | Oliver et al. (1992) |
| Subterranean clover | 91 | Ilnicki and Enache (1992) |
| Black mucuna (*Mucuna pruriens* L.), smooth rattlebox (*Crotalaria pallida* L.) | 95-99 | Skora Neto (1993) |
| Jack bean (*Canaualia ensiformis* L.), pigeon pea (*Cajanus cajan* L.) | 71-90 | |
| Cowpea (*Vigna unguiculata* L.) | 29-48 | |
| Hairy vetch | 96 | Hoffman et al. (1993) |
| Yellow mustard (*Sinapis alba* L.) | 80 | De Haan et al. (1994) |
| Annual medics (*Medicago* spp.) | 65 | Moynihan et al. (1996) |
| Annual medics (*Medicago* spp.) | 41-69 | De Haan et al. (1997) |
| Subterranean clover, white clover | 45-51 | Brandsaeter et al. (1998) |
| Velvetbean | 68 | Caamal-Maldonado et al. (2001) |
| Hairy vetch | 79 | Reddy and Koger (2004) |
| Alfalfa | 34.2-56.9 | Ghosheh et al. (2004) |
| Rye | 37-76 | Brainard and Bellinder (2004) |
| Persian clover, white clover, berseem clover, hairy vetch, alfalfa, and black alfalfa | 60.1-80.5 | Mohammadi (2009) |
| Hairy vetch | 34-50.9 | Mohammadi (2010) |

*Percentage suppression relative to a control without living mulch.

Table 1. Suppression of weeds by different living mulch species.

## 4. Factors determining the success of a living mulch system to suppress weeds

### 4.1 Living mulch species

Interseeding of a crop and living mulches have not always resulted in a positive gain (Nordquist and Wicks 1974; De Haan et al. 1997). Consequently, the success of these kinds of living mulch-crop systems is largely determined by the selection of the most appropriate species and, additionally, by the design of an optimal management strategy for the intercrop. Living mulches differ in their ability to establish well in an interseeding situation. For example, Exner and Cruse (1993) found that alfalfa (*Medicago sativa* L.) and sweet clover (*Melilotus officinalis* L.) usually established better and produced more cover than either red clover (*Trifolium pratense* L.) or alsike clover (*T. hybridum* L.) when interseeded under corn. The competitive ability against weeds is also another important characteristic determining the suitability of a plant species as a living mulch. In a study on six leguminous species (Persian clover, *Trifolium resupinatum* L.; white clover, *T. repens* L.; berseem clover, *T. alexandrinum* L.; hairy vetch; alfalfa; and black alfalfa, *M. lupulina* L.), Mohammadi (2009) found that the highest corn (as the main crop) plant traits including yield, yield components, height, leaf area index and leaf nitrogen content and the lowest weed dry weight were obtained from the plots interseeded with hairy vetch as compared with the other living mulch species (Table 2). Corn yield was increased 79% and weed dry weight was reduced 80.5% when the plots were interseeded with hairy vetch as compared with full season weedy conditions.

| Treatment | Yield (g m$^{-2}$) | Ear per plant | Seed per ear | 100-seed weight (g) | Height (cm) | Leaf area index | Leaf nitrogen content (%) | Weed dry weight (g m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|
| Weed free control | 1282.89 a | 1.20 a | 760.10 a | 32.34 a | 273.41 a | 5.10 a | 2.73 ab | 0.00 e |
| Hairy vetch | 1188.78 ab | 1.10 b | 725.30 ab | 30.94 ab | 254.83 ab | 4.82 ab | 2.88 a | 32.13 d |
| Berseem clover | 1084.31 bc | 1.05 bc | 689.08 bc | 29.86 b | 252.99 b | 4.52 abc | 2.57 bc | 49.23 bcd |
| Persian clover | 1063.37 c | 1.05 bc | 683.60 bc | 26.91 c | 247.50 b | 4.44 abc | 2.74 ab | 53.65 bc |
| White clover | 999.52 cd | 1.00 cd | 671.10 bc | 26.84 c | 248.00 b | 4.60 abc | 2.23 de | 46.33 cd |
| Black alfalfa | 945.16 d | 1.03 cd | 653.50 c | 26.78 c | 251.50 b | 3.96 c | 2.17 e | 65.73 b |
| Alfalfa | 938.08 d | 1.02 cd | 645.05 c | 27.16 c | 251.75 b | 4.19 bc | 2.41 cd | 62.15 bc |
| Weedy | 664.03 e | 0.98 d | 519.40 d | 23.49 d | 205.42 c | 3.13 d | 1.89 f | 164.78 a |
| LSD (0.05) | 109.32 | 0.07 | 63.71 | 2.27 | 20.41 | 0.74 | 0.24 | 17.21 |

Similar letters at each column indicate the non significant difference at the 0.05 level of probability.

Table 2. Means comparison of corn plant traits and weed dry weight under different living mulch treatments (from Mohammadi 2009).

Living mulches should be species that establish more rapidly than weeds and whose peak period of growth coincides with that of early weed emergence but does not coincide with that of the crop. Ideally the living mulch should suppress weed growth during the critical period for weed establishment, i.e., the period when emerging weeds will cause a loss in crop yield (Buhler et al. 2001). Beard (1973) recommended chewing fescue as a good living mulch because it adapts to the shady conditions under corn and soybean. This grass is also well adapted to dry and poor soils.

Total biomass production and nitrogen fixation are the main factors determining the suitability of leguminous species for improvement of soil fertility, but if used as a component crop in intercropping systems, competitive ability is another obvious criterion. Morphological growth characteristics, such as early relative growth rate of leaf area and earliness of height development, have been identified to determine competition in intercropping systems (Kropff and van Laar 1993).

Different phenological characteristics and growth patterns were observed among living mulches species ranging from the short-lived species *Mucuna pruriens*, which germinated quickly and covered the ground surface rapidly (LAI=1 at GDD=476°Cd), to the long-lived species *Aeschynomene histrix*, which is slow to establish and only reached a canopy LAI of 1 at around 800°Cd. These characteristics make *M. pruriens* a relatively strong competitor, which may explain its use against the perennial grass *Imperata cylindrica* in maize-based systems in Africa and North Honduras (Versteeg and Koudopon 1990; Akobundo 1993; Triomphe 1996). Based on early growth characteristics, *Crotalaria juncea*, *Cajanus cajan* and *M. pruriens* can be considered as species with a higher competitive ability than *Calopogonium mucunoides*, *Stylosanthes hamata* and *A. histrix*. This can be explained by the combination of high initial growth rates for height and leaf area development. Additionally, the high final height of *C. juncea* and *C. cajan* may confer higher competitiveness throughout the growing season (Akanvou et al. 2001).

According to De Haan et al. (1994) medics used as living mulches in row crops should be small, prostrate, and early maturing. Because of their prostrate growth habit, short life span, and good seedling vigour, medics have potential as living mulches. A living mulch should control weeds, have a relatively short growing season, provide a constant N supply, and give minimal competition to the main crop for water, light, and nutrients (De Haan et al. 1994).

In general, ideal living mulches for weed suppression should have the following characteristics:

1. Ability to provide a complete ground cover of dense vegetation.
2. Rapid establishment and growth that develops a canopy faster than weeds.
3. Selectivity between suppression of weeds and the associated crop (Teasdale 2003).

Usually, living mulches that establish an early leaf canopy cover are most competitive with weeds.

### 4.2 Living mulch planting rate and time

The success of a living mulch system also depends on appropriate management. Both time and rate of living mulch interseeding can be important factors determining the success of a crop-living mulch system. These factors are critical to reduce living mulch competition with the main crop for environmental resources while allowing the mulch to grow and cover the soil surface sufficiently to reap potential benefits such as weed suppression.

For example, interseeding rye (*Secale* sp.) or small-grain living mulches tended to provide higher levels of weed suppression when interseeded at or near planting of the main crop (Rajalahti et al. 1999; Brainard and Bellinder 2004). In another study, Mohammadi (2010) observed that the plant traits of corn and weed dry weight were not significantly influenced by hairy vetch (as a living mulch) planting times (simultaneous with corn planting or 10 days after corn emergence), but increased hairy vetch planting rate from 0 to 50 kg $ha^{-1}$ improved corn yield (by 11%) and reduced weed dry weight (by 50.9%). It was hypothesized that as living mulch density is increased, canopy closure would occur more rapidly, decreasing the amount of photosynthetically active radiation (PAR) available beneath the canopy. This would result in a concomitant decrease in weed biomass until an optimum living mulch density is achieved, beyond which, no further decrease in weed biomass could be obtained. Generally, the biomass produced by a living mulch highly depends on its planting rate. Moreover, there is often a negative correlation between living mulch and weed biomass (Akemo et al. 2000; Ross et al. 2001; Sheaffer et al. 2002). Meschede et al. (2007) expressed that the biomass accumulation by the living mulches was inversely proportional to the weed biomass. Mohammadi (2010) also reported that increasing the hairy vetch dry weight led to the reduction of weed dry weight produced. As for every 1.18 g $m^{-2}$ hairy vetch dry weight produced, 1 g $m^{-2}$ weed dry weight was reduced (Fig. 1).

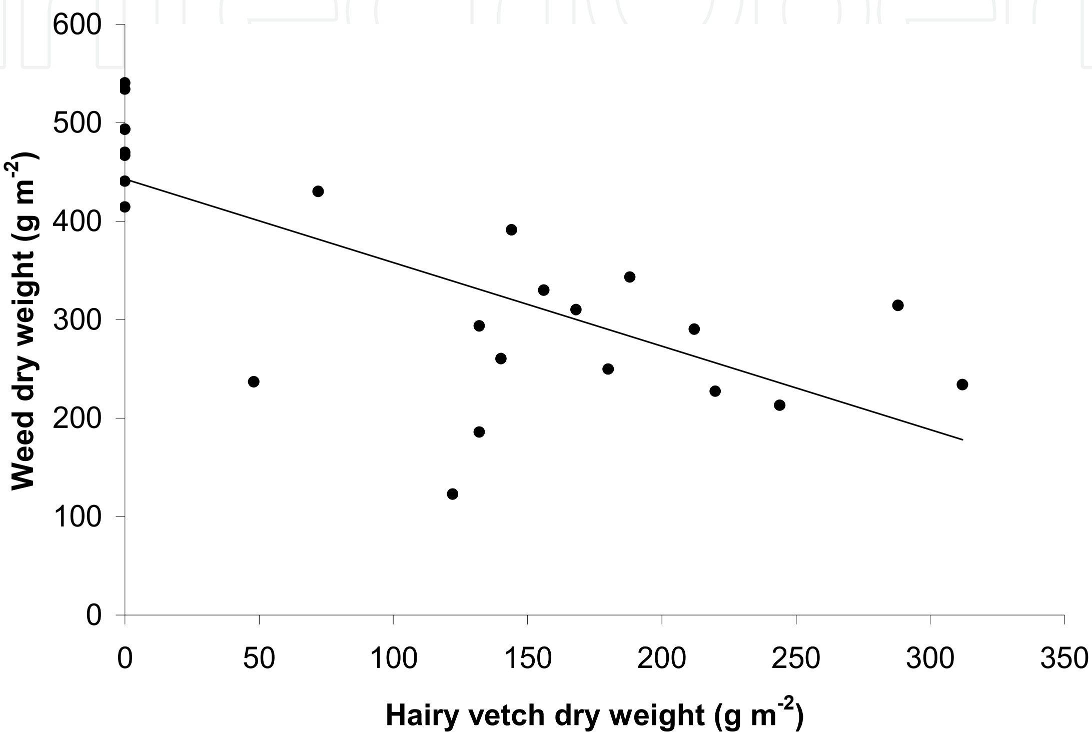


Fig. 1. Relationship between hairy vetch dry weight and weed dry weight loss in field corn as obtained using linear regression model, $y = 442.81 - 0.8485x$, $R^2 = 0.52$. The points indicate the individual weed-infested plot values (n = 24) (from Mohammadi 2010).

However, 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 as a living mulch.

Sowing time of a living mulch is also a very important factor for controlling the weed flora. Some weed species will germinate faster than the living mulch, while some of them will germinate simultaneously with mulch species and others will germinate after the living mulch. Species that germinate after the living mulch cannot grow well since the mulch species shades and mechanically blocks growth of these weed species (Kitis et al. 2011). This can lead to the alteration of weed flora in cropping systems.

## 5. Mechanisms by which living mulches can suppress weeds

There are a number of mechanisms by which living mulches can suppress weeds such as: their competition for light (Teasdale 1993; Teasdale and Mohler 1993), moisture and nutrient availability (Mayer and Hartwig 1986,); stimulating microorganisms; shading; changes in physical factors of soil such as pH, water holding capacity, temperature and aeration; and the release of allelochemicals (Leather 1983; Liebel and Worsham 1983; Putnam and DeFrank 1983; Weston et al. 1989; Yenish et al. 1995; Liebman and Davis 2000). Overall, weed suppression is thought to be based on alleopathic properties, physical impedance of germination and seedling growth, and competition for light, water, and nutrients (Teasdale, 1993; Teasdale and Mohler, 1993).

Because weed and living mulch plants compete for the same resources, weeds can be suppressed by the introduction of living mulches into cropping systems. In other words, including a living mulch in a cropping system can contribute to weed suppression by occupying the niche that would normally be filled by weeds (Teasdale 1998). Once established, living mulches can rapidly occupy the open space between the rows of the main crop and use the light, water, and nutritional resources that would otherwise be available to weeds. This can result in the inhibition of weed seed germination and reduction in the growth and development of weed seedlings. Therefore, weeds attempting to establish along with a living mulch would be in competition for resources and may not develop sufficiently. Moreover, physical impediments to weed seedlings is another mechanism by which living mulches suppress weeds (Facelli and Pickett 1991; Teasdale 1996; Teasdale and Mohler 1993).

If a living mulch becomes established before the emergence of weeds, then the presence of green vegetation covering the soil creates a radiation environment that is unfavorable for weed germination, emergence, and growth. Moreover, a more diverse biological and physical environment at the surface of soils such as that associated with living mulches offers opportunities for regulating and minimizing weed populations (Teasdale 2003).

Weed seed germination can be negatively affected by quality and quantity of light and the smaller amplitude of soil temperature fluctuation that result from the presence of living mulches (Gallagher et al. 1999; Teasdale 1998). Germination of weed seeds may be inhibited by complete light interception (Phatak 1992) by the living mulch or by secretion of allelochemicals (White et al. 1989; Overland 1966). A delay in emergence of weeds because of the presence of living mulches can also adversely affect weed seed production. Moreover, the presence of living mulches leads to greater seed mortality of weeds by favoring predators (Cromar et al. 1999). Teasdale (1998) also suggested that living-mulch suppression of weeds occurs through resource competition, promoting conditions that are unfavorable for germination and establishment, retaining living mulch residues as ground cover, and by means of allelopathy.

Water competition is another mechanism by which living mulches suppress weeds. Plants exposed to water stress for a limited time (i.e., several hours) respond by a reduction in the transpiration rate through a lowering of the leaf water potential and closing of stomata. Stomatal closing will affect the rate of leaf photosynthesis, which influences the growth and yield. However, under prolonged moisture stress (i.e., days to weeks), whole plant photosynthesis is reduced with a possibility of permanent damage to the photosynthetic apparatus (Nissanka et al. 1997). The severity of this damage will affect total dry matter accumulation and allocation among various organs of the plant. However, since most crop-living mulch systems are sufficiently supported by water and nutrients, it seems that light is the most important resource for competition between living mulches and weeds.

### 5.1 Light

Plants grown together frequently compete primarily for solar radiation (Redfearn et al. 1999). Two components of light affect the outcome of competition: quantity and quality. The quantitative component of light (i.e., intensity and amount intercepted by a plant) determines canopy photosynthesis, whereas light quality is a driving variable of plant morphology. Both aspects of light are changed in a crop–weed competition situation when compared to the sole crop or weed canopy. Most crops and weeds attain their maximum photosynthetic rates at high levels of irradiance. In a mixed crop–weed community, mutual shading of leaves causes reduction of available photosynthetic photon flux density (PPFD), which results in reduction of photosynthetic rates (Rajcan and Swanton 2001).

In general, one of the important factors of weed suppression mechanisms of living mulch is light interception. Because plants need light to develop and living mulches are blocking sunlight reaching the weeds, weed species, especially decumbent weeds, cannot get enough light for germination and growth. Kruidhof et al. (2008) reported that weed suppression is positively correlated to early light interception by the living mulch and is sustained by the strong negative correlation between cumulative light interception and weed biomass. Similarly, according to Steinmaus et al. (2008), weed suppression was linked to light interception by the mulch cover for most weed species. Caamal-Maldonado et al. (2001) also found that canopy closure of velvetbean decreased the amount of light reaching the soil and inhibited weed growth. They reported that smooth pigweed (*Amaranthus hybridus* L.) and spiny amaranth (*Amaranthus spinosus* L.), among other weeds, were well controlled by a velvetbean living mulch.

Several studies have shown that the presence and nearness of the other vegetation influences the far red/red (FR/R) ratio received by a plant ( Ballare et al. 1987; Kasperbauer 1987; Smith et al. 1990), where the FR/R ratio received by plants in a dense canopy was higher than the FR/R ratio in a sparse canopy. In fact, weeds that grow underneath or within a canopy are not only exposed to a reduced amount of PPFD, but they also receive a different quality of light than the plants grown in full sunlight. Light within the lower canopy is enriched in FR radiation (730–740 nm). This is caused by selective absorption of red light (660–670 nm) by photosynthetic pigments and FR light reflectance from and transmittance by green leaves. Chlorophyll preferentially absorbs R light and reflects FR light, thereby decreasing R/FR as sunlight moves through plant canopies. In turn, the pool of R light-absorbing phytochrome decreases relative to that of the FR light-absorbing pool, creating a signal transduction pathway that leads to an altered growth response (Rajcan and Swanton 2001). This causes the FR/R ratio of the light in the lower portion of the canopy to be higher than the FR/R ratio of the incoming light above the canopy. This may lead one to speculate that weeds growing with living mulches would have a lower root/shoot ratio than the living mulch-free condition, which would be a major disadvantage for a plant later in the season when competition for below-ground resources (such as water) may be more limiting (Rajcan and Swanton 2001). Moreover, decreased tillering may be another morphological change in weed grass species growing in this condition (Davis and Simmons 1994).

Living mulches can also change phenological development of weeds. Because FR is a determinant of photoperiod, within a dense crop canopy (FR enriched), long-day weed species may have accelerated phenological development, whereas short-day weeds (i.e., pigweed) will take longer to complete their life cycle (Huang et al., 2000). Branching and tillering are also influenced by FR light ( Begonia et al. 1988; Davis and Simmons 1994; Ghersa et al. 1994; McLachlan et al. 1993). Thus, the competitive ability of weed species would be also affected by light quality. Weed seed germination is also influenced by living mulches. It is known that light can break weed seed dormancy and stimulate germination (Hartmann and Nezadal, 1990). Therefore, including living mulches in cropping systems can prevent weed seed germination by shading the soil surface.

In general, the common important traits that determine competition for light between plants are inherent to the species. Amongst these traits are growth rate and architecture of the canopy (Davis and Garcia 1983; Kropff and van Laar 1993).

### 5.2 Allelopathy

The term allelopathy was first introduced by Hans Molisch in 1937 and refers to chemical interactions among plants, including those mediated by microorganisms. Allelopathy can be defined as an important mechanism of plant interference mediated by the addition of plant-produced secondary products to the soil rhizosphere (Weston 2005).

In certain cropping situations, allelopathy may have the potential to be integrated into a weed management plan in order to reduce the use of synthetic herbicides as well as provide other added benefits from the allelopathic crop. Allelopathy could potentially be used for weed control by producing and releasing allelochemicals from leaves, flowers, seeds, stems, and roots of living or decomposing plant materials (Weston 1996). Allelopathic compounds can be released into the soil by a variety of mechanisms that include decomposition of residues, root exudation, and volatilization (Weston 2005). They can be broadly classified into plant phenolics and terpenoids, which show great chemical diversity and are involved in a number of metabolic and ecological processes (Sung et al. 2010). These naturally produced secondary compounds can have chemical structures as complex as synthetic herbicides; they can also have the same wide range of selectivity and control for weeds (Westra 2010).

Allelopathy is another mechanism by which living mulches may suppress weeds (Fujii 1999). However, this is difficult to separate experimentally from mechanisms relating to competition for growth resources. In some situations, the allelopathic properties of living mulches can be used to control weeds. For example, the allelopathic properties of winter rye (*Secale cereale* L.), ryegrasses (*Lolium spp*), and subterranean clover (*Trifolium subterraneum* L.) can be used to control weeds in sweet corn (*Zea mays* var "rugosa") and snap beans (*Phaseolus vulgaris* L.) (De Gregorio and Ashley 1986). Root exudation produces allelopathic compounds that are actively secreted directly into the soil rhizosphere by living root systems. The allelochemicals then move through the soil by diffusion and come into contact neighboring plants. This creates a radius effect, where proximity to the allelopathic species results in greater concentrations of the allelochemical, which, in turn, typically decreases the growth of neighboring plants (Westra 2010).

Usually, using allelopathic species as a living mulch can provide normal weed suppression traits seen for mulch, as well as slowly releasing allelochemicals from their biomass which provide further weed suppression especially for weed seedling control. Therefore, if allelopathic living mulches could be incorporated in certain cropping systems to provide weed suppression, this could reduce dependency on synthetic herbicides that are potentially hazardous to our environment.

## 6. Hairy vetch as a good living mulch

Hairy vetch is a well-known living mulch in the U.S. and Europe. It provides a number of advantages in agroecosystems. Benefits include: nitrogen fixation, quick addition of biomass, prevention of soil erosion and promotion of soil porosity, amelioration of microclimate, and, primarily, weed suppression owing to its allelopathic effects (Fujii 2001). It is extensively used to suppress weeds in different cropping systems. Johnson et al. (1993) observed that hairy vetch mulch completely inhibits the weeds under a no-tillage system. According to Fujii (2001), complete weed control can be achieved by direct application of the hairy vetch to the rice (*Oryza sativa* L.) paddy fields. He suggested that hairy vetch is a promising legume in abandoned paddy fields, grasslands and orchards in the central and southern parts of Japan and its inhibitory effect toward weeds was similar to that of herbicide applications.

Oliver et al. (1992) also reported that a hairy vetch (*Vicia villosa* Roth ssp. villosa) living mulch established into soybean reduced morningglory (*Ipomoea lacunosa* L.) and spotted spurge (*Euphorbia maculata* L.) biomass by about 90% and large crabgrass (*Digitaria ischaemum* Schreb) biomass by about 70 % compared to weedy controls. When grown with the hairy vetch living mulch, soybean had yields that were comparable to a conventional production system using herbicides. In another study, Mohammadi (2010) suggested that interseeding of hairy vetch as a living mulch can be used as a beneficial method to control weeds in corn fields without causing any reduction in corn yield. In other research, best results were obtained from vetch species such as hairy vetch among living mulch species for weed control because of competitive ability, high biomass, densely growing habit, and allelopathic features of these species (Moonen and Barberi 2002; Batool and Hamid 2006; Nakatsubo et al. 2008; Mohammadi 2009).

Overall, hairy vetch is a legume living mulch that suppresses weed emergence and supplies nitrogen for sustainable cropping systems (Ngouajio and Mennan 2005; Choi and Daimon 2008) and it can be proposed as a promising candidate for an integrated weed management program.

## 7. Living mulch vs. cover crop residue

Living mulches are generally considered to be more competitive with weeds than cover crop residue because they are actively growing and can compete efficiently for water, nutrients, and light. Dead cover crop residue does not suppress weeds as consistently as living mulches (Teasdale and Daughtry 1993; Reddy and Koger 2004). Once weed 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). A living mulch competes with emerging and growing weeds for essential resources and inhibits emergence and growth more than cover crop residue does (Teasdale and Daughtry 1993; Reddy and Koger 2004).

In one study, a chemically stunted stand of crownvetch gave better weed control than dead rye mulch (Hartwig 1989). Teasdale and Daughtry (1993) found that weed suppression by live hairy vetch was more than that by paraquat desiccated cover crop residues. Therefore, weed control can be maximized by keeping hairy vetch live for a longer period rather than killing / desiccating. Living plant tissue of wheat (*Triticum* sp.), crimson clover (*Trifolium incarnatum* L.), subterranean clover and rye inhibited the emergence of weeds like ivyleaf morning glory (*Ipomoea hederacea* L.) and redroot pigweed (*Amaranthus retroflexus* L.) (Lehman and Blum 1997). However, if these were used after desiccation with glyphosate, only wheat and crimson clover were inhibitory. Likewise, subterranean clover cover crops, when used as living mulch under field conditions, can efficiently control weeds such as fall panicum (*Panicum dichotomiflorusm* Michx) and ivyleaf morning glory without affecting the yield of corn (Enache and Ilnicki 1990; Ilnicki and Enache 1992).

Several requirements for breaking dormancy and promoting germination of weed seeds in soils (light with a high red-to-far red ratio and high daily soil temperature amplitude) are reduced more by living mulches than by desiccated residue (Teasdale and Daughtry 1993). A living mulch 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 effect on this ratio (Teasdale and Daughtry 1993).

Enache and Ilnicki (1990) reported that weed biomass was reduced 53 to 94 percent by subterranean clover living mulch whereas weed biomass in desiccated rye mulch ranged from an 11 percent decrease to a 76 percent increase compared to a no-mulch control. In another study, a live hairy vetch cover crop was more effective than a desiccated cover crop in suppressing weed emergence during the first four weeks and throughout the season (Teasdale et al. 1991). In addition, if growth suppression is sufficient, a living mulch can inhibit weed seed production (Brainard and Bellinder 2004; Brennan and Smith 2005). Weed seed predation at the soil surface was also higher when living mulch vegetation was present (Davis and Liebman 2003; Gallandt et al. 2005), suggesting a role for living mulches in enhancing weed seed mortality.

Generally, it can be concluded that living mulches will suppress weeds more completely and at more phases of the weed life cycle than will cover crop residue. The inhibitory effect of typical cover crop residue or living mulch on weeds at various life cycle stages has been shown in Table 3.

## 8. Competition between living mulch and main crop

Although living mulches can efficiently suppress weeds, they may compete for nutrients and water with the main crop (Echtenkamp and Moomaw 1989) which can reduce yields. For example, Elkins et al. (1983) examined the use of tall fescue *(Festuca arundinacea* Schreb*)*, smooth bromegrass *(Bromus inermis* Leyss*)*, and orchargrass *(Dactylis glomerata* L.*)* as living mulches. They found corn yield was reduced 5% to 10% at the end of the harvest. Regnier and Janke (1990) indicated that the majority of previously conducted studies showed that the species, when selected as living mulches do not suppress weeds selectively, but suppress the crop as well; therefore, living mulches must be managed carefully to reduce their competition with the crop. In that regard, Jeranyama et al. (1998) found a reduction of 13 to 18% in grain yield when corn was intercropped with legumes. Norquidst and Wicks (1974) found corn dry matter yield to be reduced by up to 47% and grain yield by up to 31% when alfalfa was interseeded at the time of corn establishment. Hoffman et al. (1993) observed a corn reduction of over 76% in corn grown with untreated hairy vetch.

| Weed life cycle stage | Cover crop residue | Living mulch |
|---|---|---|
| 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 effects on these processes.
[b] When living mulches are combined with other practices such as soil disturbance or mowing, perennial structure survival may be more effectively reduced.

Table 3. Potential impact of typical cover crop residue or living mulch on inhibition of weeds at various life cycle stages (from Teasdale et al. 2007).

Typically, a living mulch that is competitive enough to suppress weeds will also suppress crop growth and yield. Much of the research with living mulches has focused on documenting and alleviating this problem (Liebman and Staver 2001; Teasdale, 1998). Many studies in the North Central U.S. on legume interseeding in established corn stands report grain yield losses that are attributed to moisture stress (Kurtz et al. 1952; Pendleton et al. 1957), N deficiency (Scott et al. 1987; Triplett 1962), and reduced corn populations associated with wider row spacing (Schaller and Larson 1955; Stringfield and Thatcher 1951). Marks (1993) also suggested that reduced growth of the main crop may be due to competition for water or some other limited resource, or the mulch may be having an allelopathic effect.

De Haan et al. (1997) used burr medic (*Medicago polymorpha* L.) and snail medic [*Medicago scutellata* (L.) Mill.] as living mulches in corn and found that, although both medics suppressed weeds, corn and medics competed strongly for resources. Consequently, medic living mulches significantly reduced corn grain yields. The reduction was due to competition for nutrients or moisture when medic and corn were planted at the same time. Yield loss in transplanted cabbage due to competition with the living mulch for light or moisture was also recorded by Bottenberg et al. (1997).

When the growth of a living mulch is not restricted, or when soil moisture is inadequate, even a relatively vigorous crop like potato may suffer competition and loss of yield (Rajalahti and Bellinder 1996). Generally, without irrigation, it becomes more challenging to implement a living mulch system. However, there are successful examples of annual or biennial living mulches established after emergence of the main crop, which gives the main crop a competitive advantage (Scott et al. 1987; Wall et al. 1991). If living mulches are established before or after the main crop is planted, competition of the living mulch for water may reduce crop yields (Echtenkamp and Moomaw 1989; Eberlein et al. 1992; Masiunas et al. 1997; Teasdale et al. 2000). Thus, it can be concluded that living mulches can severely compete with the main crop for water which is particularly problematic during a dry period. In one study, corn yields were not negatively affected by competition from the crownvetch, birdsfoot trefoil (*Lotus corniculatus* L.), and flatpea (*Lathyrus sylvestris* L.) living mulches in years with adequate precipitation. However, in a year with very low rainfall in July and August, crownvetch and birdsfoot trefoil reduced corn yields (Duiker and Hartwig 2004).

In general, although legume living mulches compete weakly with cereals for light, N, phosphorus (P), and K, they can compete strongly for water. If water stress is eliminated by irrigation, living mulches of legumes rarely reduce and sometimes increase main crop yields (Grubinger and Minotti 1990; Fischer and Burrill 1993; Costello 1994).

## 9. The ways to prevent or reduce the competition between living mulch and main crop

A serious problem in living mulch cropping systems is reduced main crop yield because of competition. Management of living mulches becomes critical to reduce competition with the main crop for resources while allowing the mulch to grow sufficiently to reap potential benefits. Different ways have been suggested to overcome this problem in such cropping systems. One of them is the selection of suitable living mulch species and the others have been employed to suppress the living mulch, such as tillage, mowing, and herbicides (Grubinger and Minotti 1990; Fischer and Burrill 1993; Costello 1994; Martin et al. 1999; Zemenchik et al. 2000).

### 9.1 Selection of suitable species

It is important to make the correct choice of a living mulch (Ingels et al. 1994). According to Ilnicki and Enache (1992), to avoid competition with the main crop in the subterranean clover cropping system, it is essential to use species and cultivars which have a low canopy height and terminate vegetative growth early in the summer. Greater potential benefits might be expected from living mulches with a very different active growth period than the main crop. For example, kura clover does not produce abundant dry matter during dry periods of the growing season and should therefore compete less than other perennial legumes with corn for limited resources, especially water (Zemenchik et al. 2000). Kura clover and corn in the living mulch systems were more compatible after tasselling because the species differed greatly in stature and corn had sequestered much of the resources necessary to complete its life cycle. This ecological differentiation is a necessary condition for coexistence according to the competitive exclusion principle (Hardin 1960).

Another approach suggested by Ilnicki and Enache (1992) was to use winter annual legumes, e.g., subterranean clover, as a living mulch. Winter annual legumes sown in late summer grow vegetatively during autumn, become dormant in winter, and resume vegetative growth the following spring. Later in the spring or early summer the plant flowers, senesces, and dies. Because of this unique life cycle, a main crop transplanted into the senescencing mulch would be able to use all available water and nutrients.

Moynihan et al. (1996) reported that black medic was found to be the least competitive medic species when it was intercropped with barley as a living mulch. In another study, black medic did not significantly reduce corn yields compared with the medic and weed-free check, whereas all other species caused significant yield reductions. Therefore, it is suited to this system because it does not grow aggressively early in the year when it could reduce corn yield.

Newenhouse and Dana (1989) also evaluated different grass living mulches for strawberries (*Fragaria* sp.) and found perennial ryegrass (*Lolium perenne* L.) was best because it covered the ground quickly but did not spread into the crop rows. In raspberries (*Rubus* sp.), a white clover (*Trifolium repens* L.) living mulch did not affect the crop but perennial ryegrass reduced berry yield (Freyman 1989).

According to Akanvou et al. (2001), slow-growing species with longer duration such as *Stylosanthes hamata* and *Aeschynomene histrix* are expected to be less competitive and therefore appropriate for early establishment in rice-legume intercropping systems. Intercropping research has shown that most legumes do not compete strongly with cereals for light, N, P, and K, whereas they compete equally for water (Ofori and Stern 1987; Vandermeer 1990). The low stature of most legumes and their horizontally positioned leaves reduce competition for light with tall, erect cereals. Since many legumes are $C_3$ crops with low light saturation points and low temperature optima, one might expect these legumes to complement a $C_4$ crop such as corn that has a high light saturation point and high temperature optimum (Ofori and Stern 1987). Instead of competing for N, legumes may instead contribute N to the main crop (Fujita et al. 1992). Because of their different root systems (less fibrous and often having a taproot), competition for the immobile nutrients P and K can be expected to be limited (Ofori and Stern 1987; Vandermeer 1990). Legumes are therefore promising candidates for living mulches in agroecosystems.

Generally, the competitive ability is an obvious characteristic determining the suitability of a plant species as a living mulch. For example, tall and vigorously growing legumes with relatively large leaves and rapid leaf expansion might be detrimental to the associated crop, whereas poorly competing species will be out-competed and will therefore contribute little to improving soil fertility (Akanvou et al. 2001).

### 9.2 Application of appropriate practices

Appropriate management is essential to avoid or decrease the interspecific competition between intercropped species. Several approaches have been used to reduce competition between the living mulch and main crop species without eliminating the desirable attributes and benefits of the living mulch.

The classical attempts to reduce competition in living mulch systems have focused on chemical or mechanical suppression of mulch growth or screening for less competitive living mulches. Reducing interference between a white clover living mulch and sweet corn (*Zea mays* L. var. *saccharata*) by chemical suppression or mechanical suppression has been reported by Vrabel (1983) and by Grubinger and Minotti (1990), respectively. Reduced interference by mechanical suppression of white clover and subterranean clover living mulches in white cabbage (*Brassica oleracea* var. *capitata* L.) is also reported by Brandsæter et al. (1998).

Timely mowing of a clover (*Trifolium spp*.) living mulch prevented the competition in transplanted broccoli (*Brassica oleracea* L.) (Costello and Altieri 1994). Ilnicki and Enache

(1992) also found that mowing of a subterranean clover mulch was necessary to reduce early competition when sweet corn, tomato (*Lycopersicon esculentum* Mill.) and cabbage crops were planted into it. Mulongoy and Akobundo (1990) proposed the use of growth retardants to reduce growth of the associated legumes in maize. Werner (1988) investigated the influence of different living mulch species on weed density and diversity. Weed numbers were reduced and maize yield was not affected where growth of the living mulch was reduced by cutting or flaming treatments.

Another way to avoid or decrease the competition in such systems is to intercrop a main crop and a living mulch with a synchronized onset of maximum vegetative growth. This synchronization of living mulch and main crop could be achieved in different ways (Brandsæter and Netland 1999). Muller-Scharer and Potter (1991) concluded that living mulches should be seeded to emerge in the middle of the vegetation period of the main crop. De Haan et al. (1994) have studied the opposite way to avoid interference problems in living mulch systems in the north central region of the U.S.. They tried to develop a spring-seeded living mulch that had been selected for its ability to suppress weeds without affecting crop yield. This living mulch flowered 3 weeks after emergence and began senescence 5 weeks after emergence.

Shifting the relative sowing dates of the various intercropped components in a crop-living mulch system is an important means to ensure a better use of available resources and to minimize yield loss of the main crop (Midmore 1993). Usually, delaying the sowing time of living mulches might reduce the interaction effects. For example, velvetbean planted as living mulch 20 days after corn reduced weed biomass by 68% with no negative effects on corn yield (Caamal-Maldonado et al. 2001). Corn grain yield was not reduced when living mulch seeding was delayed until the corn was 15 to 30 cm in height (Scott et al. 1987), suggesting that yield can be maintained by delaying the seeding date of the living mulch. In another study, annual medics interseeded several weeks after corn planting did not affect corn yield (De Haan et al. 1997). Moreover, delaying the planting time of the main crop until senescing of living mulch might also decrease the interspecific competition. For example, competition was not a problem when dwarf beans (*Phaseolus vulgaris* L.) were planted into a clover mulch as it began senescing (Ilnicki and Enache 1992).

In general, the efficient management approaches to prevent or reduce the competition between living mulches and a main crop include:

1. Using low-growing living mulch that competes primarily for light. In this case, as long as the living mulch becomes established before the weeds, it would maintain weed suppression by excluding light but would not impact taller growing crops and would not compete with the crop excessively for soil resources such as water and nutrients.
2. Timely planting the living mulch so that the time of peak growth of the living mulch does not coincide with the critical period during which competition would have the greatest impact on main crop yield.
3. Reducing crop row spacing and/or increase crop population to enhance the competitiveness of the main crop relative to the living mulch.
4. Providing supplemental water and nitrogen to compensate for resources used by living mulch plants. Usually, soil moisture depletion by living mulches will become the primary management consideration in those areas of the world where soil moisture is

the limiting factor in crop production. Therefore, preparation of sufficient water for these cropping systems is very essential.

5. Suppressing the living mulch so as to reduce its competitiveness with the crop using the following methods:

a. A broadcast application of an herbicide at a rate that is suppressive but not lethal.
b. A banded application of a herbicide to kill the living mulch in the crop row so as to reduce competition within the row area but permit weed suppression by the living mulch between rows.
c. Strip tillage to provide suitable planting conditions without competition within the crop row but to permit weed suppression by the living mulch between rows.
d. Timely mowing to reduce the height and vigour of the living mulch (Teasdale 2003).

It can be concluded that although living mulches are efficient tools to suppress weeds in cropping systems, but an appropriate management program is very essential to reduce the competition with the main crop for environmental resources and enhance the potential benefits of living mulch such as weed suppressing ability.

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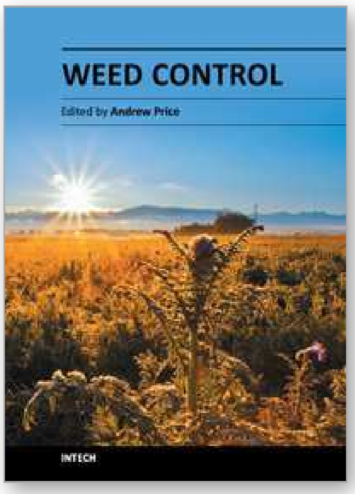


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Crop loss due to weeds has challenged agricultural managers since man began to develop the first farming systems. In the past century, however, much progress has been made to reduce weed interference in crop settings through effective yet mostly non-sustainable weed control strategies. With the commercial introduction of herbicides during the mid-1900's, advancements in chemical weed control tactics have provided efficient suppression of a broad range of weed species for most agricultural practices. Currently, with the necessity to design effective sustainable weed management systems, research has been pushing new frontiers on investigating integrated weed management options including chemical, mechanical as well as cultural practices. Author contributions to Weed Science present significant topics of research that examine a number of options that can be utilized to develop successful and sustainable weed management systems for many areas of crop production