Integrated management of living mulches for weed control: A review

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Review

Abstract

Living mulches are cover crops grown simultaneously with and in close proximity to cash crops. Advantages of living mulches over dead cover crops may include increased weed suppression, reduced erosion and leaching, better soil health, and greater resource-use efficiency. Advantages of living mulches over synthetic mulches may include enhanced agroecosystem biodiversity and suitability for a wider range of cropping systems. A major disadvantage of this practice is the potential for competition between living mulches and cash crops. The intensity and outcome of mulch-crop competition depend on agroecosystem management as well as climate and other factors. In this review, we consider the management of living mulches for weed control in field and vegetable cropping systems of temperate environments. More than 50 yr of research have demonstrated that mechanical or chemical suppression of a living mulch can limit mulch-crop competition without killing the mulch and thereby losing its benefits. Such tactics can also contribute to weed suppression. Mechanical and chemical regulation should be combined with cultural practices that give the main crop a competitive advantage over the living mulch, which, in turn, outcompetes the weeds. Promising approaches include crop and mulch cultivar selection; changes to planting time, density, and planting pattern; and changes to fertilization or irrigation regimes. A systems approach to living mulch management, including an increased emphasis on the interactions between management methods, may increase the benefits and lower the risks associated with this practice.

Introduction

Living mulches are annual or perennial cover crops grown during the growing season of the main (cash) crop. Numerous studies have documented the capacity of living mulches to diminish the need for intensive tillage, reduce soil erosion and nitrate leaching, and improve soil health (Andrews et al. 2020; Hartwig and Ammon 2002; Leary and DeFrank 2000; Qi et al. 2011; Siller et al. 2016). For example, Hall et al. (1984) reported that two legume living mulches, crownvetch [*Securigera varia* (L.) Lassen] and birdsfoot trefoil (*Lotus corniculatus* L.), generally reduced erosion in no-till corn (*Zea mays* L.) relative to a dead mulch of corn stover residue. Living mulches also increase agroecosystem biodiversity, which is frequently associated with improved disease, insect, and weed management (Malézieux et al. 2009; Petit et al. 2018).

Weed suppression is among the most important functions of living mulches. Living mulches tend to provide improved weed control relative to terminated cover crops because they can suppress weeds through multiple mechanisms and throughout weed life cycles (Teasdale et al. 2007). Mechanisms of weed suppression by living mulches include inhibition of weed seed germination by shading, competition for light and belowground resources, and allelopathy (Médiène et al. 2011; Petit et al. 2018; Teasdale 1996; Weston 1996). Harvested intercrops may perform similar functions, but living mulches selected primarily for weed suppression often achieve this goal more effectively than intercrops selected primarily for harvest benefits (Liebman and Dyck 1993). Although synthetic mulches can provide effective weed suppression, they may be associated with environmental concerns (e.g., persistence and disposal) and may be prohibitively expensive for extensively grown field crops (Grundy and Bond 2007; Norsworthy et al. 2012).

The primary drawback associated with living mulches is their tendency to suppress main crops. Most living mulches that have the ability to suppress weeds also have the ability to suppress crops (Teasdale 1996). Crop suppression may involve allelopathy (Walters and Young 2008) but typically occurs through competition for resources (Liebman et al. 2001; Teasdale 1998). When living mulches compete excessively with main crops, they may cause unacceptable yield losses. In an extreme example, Eberlein et al. (1992) reported that an

unsuppressed alfalfa (*Medicago sativa* L.) living mulch could cause corn yield losses greater than 96% under nonirrigated conditions. White and Scott (1991) reported that second-year legume living mulches reduced winter wheat (*Triticum aestivum* L.) yield by approximately 70% (average of six perennial legumes, spring top-dressed nitrogen treatment). However, living mulches do not always reduce main crop yield (Teasdale 1998) and may even increase yield. In one study, herbicide-suppressed living mulches of white clover or ladino clover (both *Trifolium repens* L.) increased marketable sweet corn yield by 75% (Vrabel et al. 1981). These divergent outcomes are partially explained by differences in living mulch species and management practices. It is possible to promote both weed suppression and main crop yield by selecting appropriate living mulches and managing them in ways that capitalize on the morphological, physiological, and developmental differences among main crops, living mulches, and weeds (De Haan et al. 1994; Liebman et al. 2001; Verret et al. 2017).

Research on the management of living mulches began as early as the 1960s and intensified in the 1970s and 1980s (Hughes and Sweet 1979; Paine and Harrison 1993). In subsequent decades, this research continued without leading to widespread adoption, perhaps because no-till planting of herbicide-resistant crops into killed sods provided some of the same benefits with reduced risks to yield. However, excessive use of herbicides carries risks of its own, including environmental harm and the emergence of resistant weeds (Mortensen et al. 2012; Norsworthy et al. 2012). In recent years, interest in living mulches has again increased because living mulch systems can contribute to agricultural sustainability through reduced herbicide inputs and improved soil health (Bartel et al. 2020; Moore et al. 2019; Robačer et al. 2016). Despite these benefits, the widespread use of living mulches remains limited by several barriers (Sheaffer and Moncada 2012 p. 354; Vincent-Caboud et al. 2017; Wezel et al. 2014), including ongoing uncertainty about best management practices.

This review focuses on the management of living mulches grown alongside field or vegetable crops in temperate environments for the primary purpose of weed suppression. Our goal is not to describe the benefits of living mulches, many of which are summarized in articles cited above. Instead, we evaluate cultural, mechanical, and chemical methods of maximizing weed suppression and minimizing mulch-crop competition (Figure 1). The purpose of this review is to characterize management practices that can increase the likelihood of positive outcomes (good weed suppression and main crop yield) in living mulch systems. Although few generalizations apply to every living mulch system, we seek to identify emerging trends in the management literature and draw attention to remaining knowledge gaps.

Living Mulch Species

In this review, we define living mulches as plants grown alongside main crops for noncommercial benefits that occur during the main crop growing season. Living mulch biomass is returned to the soil rather than being harvested. This functional definition does not include morphological, physiological, or developmental traits, which vary widely among successful living mulches. However, living mulches useful for weed control do share some general characteristics. Living mulches that provide dense ground cover early in the growing season can prevent weed establishment (Nicholson and Wien 1983; Teasdale 1998). For this reason, many living mulches are either perennial species or annual species with rapid initial growth. Because competition for light is largely

asymmetric (Weiner 1990), it is important that living mulches remain short to prevent excessive competition against the main crop (De Haan et al. 1994; Echtenkamp and Moomaw 1989; Leoni et al. 2020). If mechanical or chemical tactics are used to limit living mulch height, living mulches must recover from these control measures more quickly than weeds. The remainder of this section provides more detail on living mulch traits, then notes that different living mulches are appropriate for different cropping systems.

Most living mulches are legumes or grasses, although brassicas and other species, such as purslane (*Portulaca oleracea* L.), are also used (Ellis et al. 2000; Masiunas 1998; Teasdale 1998). Legume living mulches are notable for their ability to add nitrogen to the cropping system, but the in-season and post-season availability of fixed nitrogen to crops may vary (Germeier 2000; Hartwig and Ammon 2002; Liebman and Davis 2000; Sanders et al. 2017; Singer and Pedersen 2005; Triplett 1962). Although nitrogen fixation represents a useful benefit, it is possible for legume living mulches to increase nitrogen availability to weeds and thereby exacerbate weed issues over time (Sjursen et al. 2012). Grasses may offer advantages such as ease of maintenance (Elkins et al. 1983). Cool-season grasses lose vigor in the summer, potentially reducing the need for or difficulty of additional suppression (Adams et al. 1970; Elkins et al. 1979). Because weed control improves with cropping system diversity (Liebman and Dyck 1993), some research has tested mixtures of living mulch species (Echtenkamp and Moomaw 1989; Hartwig and Hoffman 1975). However, such mixtures may be difficult to manage.

Annual and perennial living mulches should be selected according to different criteria and offer different advantages. Ideotypes for spring-seeded living mulches often specify that establishment should be rapid (Buhler et al. 1998; De Haan et al. 1994). In contrast, the ideotype of a perennial living mulch could include delayed green-up in the spring to reduce mulch-crop competition (Flynn et al. 2013). Leoni et al. (2020) tested 11 commercial cultivars of legumes in Italy and concluded that self-seeding annuals offer rapid and complete establishment, but perennial mulches might provide the best weed control. Perennial living mulches are particularly suitable for no-till or low tillage systems, although annual species can also reduce tillage by eliminating the need for interrow cultivation during the growing season. Once established, perennial living mulches may be more difficult to suppress. For example, Cardina and Hartwig (1980) found that a crownvetch living mulch became more tolerant of herbicides with age. In addition to being easier to suppress, relative to established perennial living mulches, annual living mulches give the grower more control over planting and termination times. Annual living mulches are sometimes intended to reseed themselves (Teasdale 1996), but can be terminated before seed set to prevent volunteer plants from emerging in the next season.

When choosing living mulch species and management programs, growers should consider the main crop's ability to tolerate competition. For example, Ziyomo et al. (2013) reported an interaction between corn hybrid and kura clover (*Trifolium ambiguum* M. Bieb.) control on grain yield in Minnesota and Wisconsin, USA. Drought-susceptible hybrids showed yield reductions in a living mulch relative to a killed mulch. Moynihan et al. (1996) tested multiple medic species (*Medicago* spp.) as intercrops in barley (*Hordeum vulgare* L.) in Minnesota and concluded that this system was more successful with a conventional-height barley cultivar than a semi-dwarf cultivar. Uchino et al. (2016) found substantial differences among eight soybean [*Glycine max* (L.) Merr.]
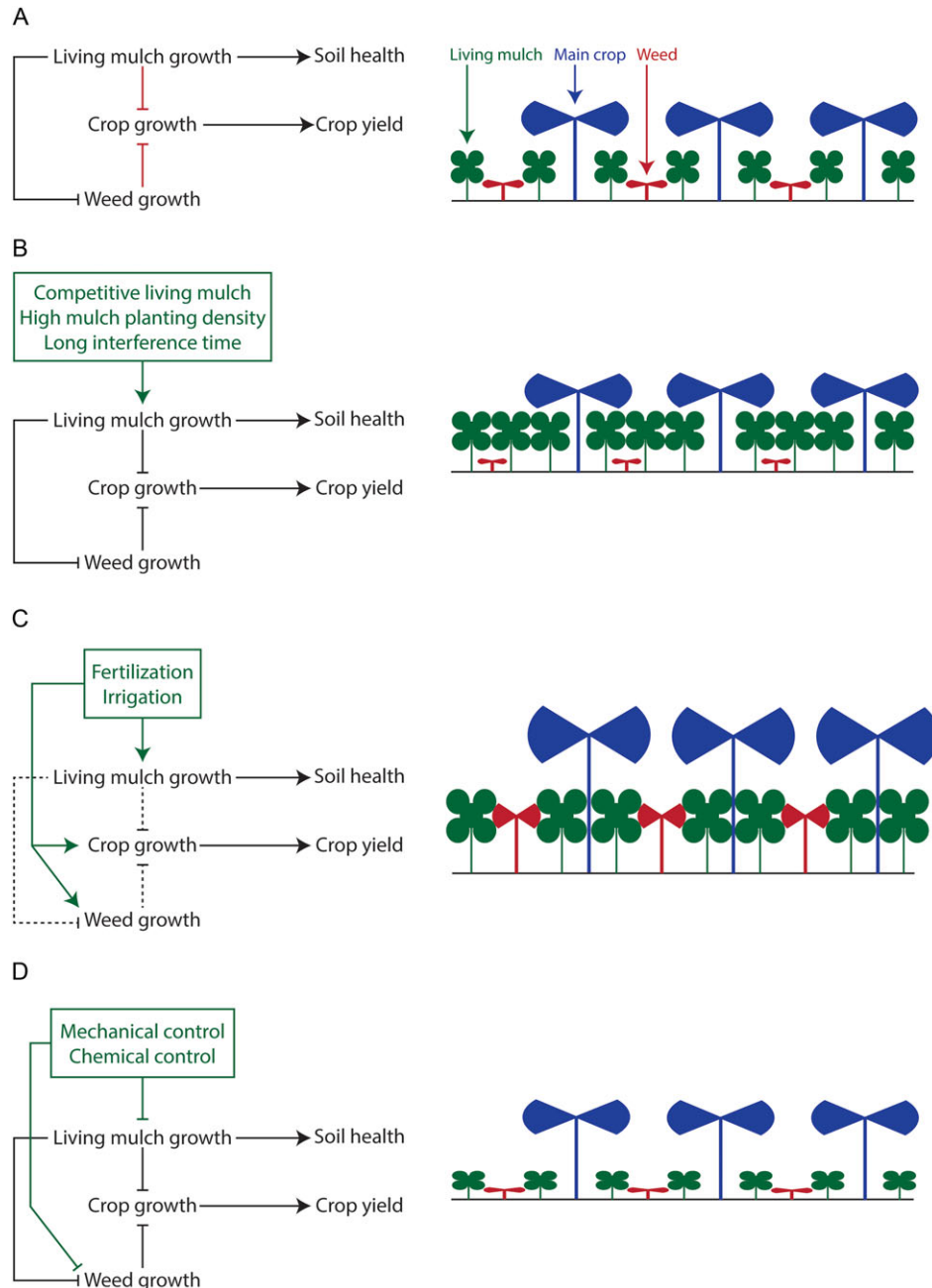
Figure 1. Purpose and methods of living mulch management. (A) Managers seek to reduce mulch and weed suppression of crop growth (red arrows) without eliminating the positive effects of the living mulch. (B–D) Management practices have both direct effects (green arrows) and indirect effects (black arrows). (B) Increasing the competitiveness of a living mulch strengthens its effects, both positive and negative. (C) Fertilization and irrigation may benefit any plant species, although unequal benefits often affect competitive dynamics. When resources are less limited, interspecific competition may be weaker (dotted lines). (D) Mechanical and chemical tactics are used to suppress the living mulch and provide supplemental weed control. In graphics, the main crop is shown in blue, the living mulch as the green clover, and the weed in red.

varieties grown for forage in an Italian ryegrass (*Lolium multiflorum* Lam.) living mulch in Japan. The living mulch usually reduced whole-plant yield, but this reduction was larger in early-maturing than late-maturing soybean varieties. Taken together, these findings indicate that main crops vary in their yield responses to competition from living mulches. Whenever possible, main crops for living mulch systems should be competitive (e.g., tall-statured) and tolerant of resource limitation (e.g., drought resistant).

Comprehensive field screening of living mulch species and cultivars is a good way to identify suitable candidates for a particular cropping system and geographic area. For example, studies in Connecticut, USA, revealed that an annual grass, field brome (*Bromus arvensis* L.), yielded more marketable snap bean (*Phaseolus vulgaris* L.) and sweet corn than other living mulch candidates selected from an initial group of 57 possibilities (DeGregorio and Ashley 1985, 1986). In New York, USA, Nicholson and Wien (1983) tested five turfgrasses and three white clover cultivars from an initial group of 82 grasses and legumes. They found that Chewing's fescue (*Festuca rubra* L.), Kentucky bluegrass (*Poa pratensis* L.), and the white clover cultivar 'Kent'

provided some ground cover without reducing sweet corn or cabbage (*Brassica oleracea* L.) yield. In Norway, subterranean clover (*Trifolium subterraneum* L.) exhibited traits desirable in a living mulch, although hairy vetch (*Vicia villosa* Roth) may be preferred for its superior frost resistance in that region (Brandsæter et al. 2000; Brandsæter and Netland 1999). In southern Sweden, Bergkvist (2003a) reported substantial differences between white clover varieties established in barley and maintained in winter wheat or winter oilseed rape (*Brassica napus* L.). In the first year, the clover variety 'AberCrest' did not reduce wheat or high-density rape yields, but the variety 'Sonja' reduced wheat yield by approximately one third and nearly eliminated the rape yield.

The choice of living mulch species should reflect several factors, including cropping system, climate, and grower priorities (e.g., willingness to use tillage or herbicides). In general, living mulches should be capable of quick initial growth. They should be competitive against weeds and recover well from field management operations. A manageable, short-statured growth habit should not interfere with the main crop canopy. Ideally, growers should choose living mulch species and main crops from different families to promote pest control and functional diversity.

Interference Time

The timing of living mulch planting relative to main crop planting is a crucial influence on the intensity and outcome of mulch-crop competition. Delayed planting is generally a reliable method of reducing competition with the main crop, but often comes at the cost of reduced early-season weed control (Liebman et al. 2001) and soil cover. Some workers reserve the term "living mulch" for cover crops that are established before main crop planting and use "smother crop" for later planting times (Liebman et al. 2001). We do not draw that distinction here. Instead, we apply "living mulch" to any cover crop grown for a significant portion of the main crop growing season (i.e., several growth stages) with the intention of providing nonharvest benefits within the growing season. If an interseeded cover crop is primarily intended to provide postharvest benefits rather than weed control and other ecosystem services within the growing season of the main crop, it is best to avoid the label "living mulch."

When a living mulch is planted near the beginning of the main crop growing season, a delay in living mulch planting usually decreases both weed control and the risk of main crop yield losses. In New York, USA, Brainard and Bellinder (2004) reported that rye (*Secale cereale* L.) seeded at the same time as broccoli (*Brassica oleracea* L.) transplanting effectively suppressed weeds, but broccoli yield was reduced relative to a weed-free control. In contrast, rye seeded 10 or 20 d after broccoli transplanting did not control weeds or reduce broccoli yield. Brainard et al. (2004) found that hairy vetch and lana vetch (*Vicia villosa* Roth) reduced cabbage yield when seeded 10 d after transplanting, but there was no yield penalty associated with seeding at 20 or 30 d. A delay in living mulch planting has also been reported to increase crop yield in other broccoli systems, as well as cauliflower (*Brassica oleracea* L.), leek (*Allium porrum* L.), pepper (*Capsicum annuum* L.), pumpkin (*Cucurbita pepo* L.), and tomato (*Solanum lycopersicum* L.; see Adamczewska-Sowińska et al. 2009; Adamczewska-Sowińska and Kołota 2008; Canali et al. 2015; Ciaccia et al. 2017; Kloen and Altieri 1990; Kołota and Adamczewska-Sowińska 2004; Montemurro et al. 2017; Müller-Schärrer et al. 1992; Vanek et al. 2005). Similarly, delayed living mulch planting may reduce yield losses in field crops,

including corn and soybean (Brooker et al. 2020; Uchino et al. 2009; Vrabel et al. 1980; Wivutvongvana 1973).

If living mulches are planted late, it may be possible to avoid excessive weed pressure by implementing additional weed control measures in the period before living mulch establishment (Brainard and Bellinder 2004; Kunz et al. 2016). This approach is a good option for growers seeking to reduce the risk of main crop yield losses, but it is not the right choice in every situation. Drawbacks of late planting include any costs and soil displacement associated with the additional weed control measures, as well as reduced living mulch biomass accumulation. Conversely, earlier planting can lead to better establishment of the living mulch and improved ground cover, which are desirable when living mulches are not strongly competitive (Abdin et al. 1997, 2000). Earlier planting may also reduce soil erosion at the beginning of the season, when maximum rainfall is expected in many temperate regions.

Two special cases merit additional attention. First, in the establishment year for perennial living mulches, earlier planting may promote stronger establishment. For example, fall seeding of white clover can provide better ground cover than spring seeding for the corn growing season (Cooper 1985). The living mulch must be suppressed in both the establishment year and subsequent years to prevent yield losses (Cooper 1985; Peterman 1985). A second special case occurs when an annual or perennial living mulch is established during the season before main crop planting. In this case, the timing of main crop planting may affect the intensity of competition. For example, Hoffman et al. (1993) found that fall-planted hairy vetch, which began to senesce in June, decreased yield by more than 76% in April-planted corn but did not compete strongly with May-planted or June-planted corn in Ohio, USA. Alternatively, delayed main crop planting could allow sod species to become larger and therefore more difficult to suppress at planting time (Peters and Currey 1970). However, given the numerous constraints on crop planting dates in commercial systems (e.g., weather, labor, and equipment availability), adjusting main crop planting dates may not be a realistic method of minimizing mulch-crop competition.

Another method of shortening the period of living mulch interference involves killing the mulch within the growing season. Like a delay in living mulch planting, this method may reduce competition against the main crop. Afshar et al. (2018) found that living mulches did not reduce sugarbeet (*Beta vulgaris* L.) yield if they were terminated at the sugarbeet V2 growth stage in Montana, USA. To protect onion (*Allium cepa* L.) yield in North Dakota, USA, a barley living mulch should not be allowed to grow taller than 18 cm (approximately 4 or 5 wk; Greenland 2000). Zandstra and Warncke (1993) tested seeding rates and cutting times for barley and rye in onion and carrot (*Daucus carota* L.) in Michigan. Barley seeded at 67.3 kg ha^{-1} and killed at 10 cm provided good soil cover without excessive mulch-crop competition. In corn, hairy vetch has been shown to provide some weed control without inhibiting corn growth if controlled within 2 wk of corn planting (Czapar et al. 2002). De Haan et al. (1994) used yellow mustard (*Sinapis alba* L.) under various management regimes to identify characteristics of an optimal living mulch system for corn in Minnesota. They reported that 4 wk represented a promising duration for interference. However, Buhler et al. (2001) found that killing sava medic [*Medicago scutellata* (L.) Mill.] 30 d after planting reduced weed control without improving corn yield in Iowa, USA. Early termination of living mulches, like late planting, is most likely to be useful when mulch-crop competition is strong.

To summarize, main crop yield losses are more likely when living mulches are planted earlier (relative to the main crop) and not terminated within the main crop growing season. Established living mulches are especially likely to outcompete slow-growing main crop seedlings (perennial main crops are less vulnerable after the establishment year). To reduce this competitive pressure, growers can plant annual living mulches later in the growing season. Delayed planting of living mulches will reduce their ability to provide benefits, including weed control. Optimal living mulch planting dates vary across systems, although simultaneous planting of living mulches and main crops sometimes works well. Living mulches can be terminated within the main crop season if mid- or late-season competition is likely to reduce main crop yield. In annual living mulch systems, living mulch establishment and termination times can also be adjusted to reduce interference with other field operations.

Planting Density and Pattern

The density of a living mulch influences its competition with the main crop as well as its ability to provide weed control and other services (Figure 1B). Experiments on living mulch seeding rate have reported three different outcomes. First, crop yield may decline with increasing living mulch density, particularly when resources are limited (Ateh and Doll 1996; Pouryousef et al. 2015). This finding reflects excessive mulch-crop competition at high living mulch density. Alternatively, crop yield can increase with living mulch density in situations in which weed pressure is expected to be severe (Kaneko et al. 2011). A third outcome occurs when low and high living mulch seeding rates result in similar crop yields (De Haan et al. 1997; Mohammadi 2010). This outcome could indicate that the competitive effects of living mulch plants on the main crop are similar to the competitive effects of the weeds that they replace.

Like living mulch planting density, living mulch planting pattern and planting method may affect competitive dynamics and main crop yield. Vrabel et al. (1980) reported excessive competition between corn and legumes broadcast across the entire plot at planting time, but no yield reduction occurred if the legumes were instead seeded in 0.45-m strips between the corn rows. In contrast, Buhler et al. (2001) found that the planting pattern of sava medic (band between rows, band over rows, or broadcast) had little effect on giant foxtail (*Setaria faberi* Herrm.) control or corn yield when the medic was allowed to grow to maturity. Echtenkamp and Moomaw (1989) reported that drilling cover crops between rows of standing corn resulted in improved establishment over a broadcast treatment in one of two years. This result was associated with increased rainfall relative to the other year, in which rainfall was adequate and no difference between drilling and broadcast treatments was observed. Broadcast seeding might also increase the risk of living mulch seed predation relative to other planting methods. Invertebrate seed predators are likely to consume broadcast cover crop seeds (Youngerman et al. 2020).

In some field situations, the planting pattern and density of the main crop are more influential than those of the living mulch. In cabbage, Lotz et al. (1997) showed that a decreased row distance could reduce the yield losses associated with a clover (*Trifolium* spp.) living mulch. Other studies have focused on determining optimal row widths and within-row spacings for corn (Harper et al. 1980; Pendleton et al. 1957; Wivutvongvana 1973). Fischer and Burrill (1993) reported that narrowing corn rows to the point of a near-equidistant planting arrangement (row width similar to

spacing within rows) helped the corn compete with the living mulch. Alternatively, corn may be planted in paired rows, which are intended to facilitate access to the living mulch (e.g., for mechanical suppression) and perhaps reduce interspecific competition (Grubinger and Minotti 1990; Jellum and Kuo 1990). A more recent study, which accounted for potentially mineralizable nitrogen and clover persistence as well as corn grain yield, recommended planting corn in 90-cm rows on top of 20-cm herbicide bands applied to a white clover mulch (Sanders et al. 2017). Extension recommendations have suggested increasing corn and soybean seeding rates by 10% because an established legume living mulch may interfere with planter operation and seed placement (Singer and Pedersen 2005). Increased seeding rates may not be necessary if legume or grass living mulches are planted later. Working with organic corn in the northeastern United States, Youngerman et al. (2018) suggested that interseeding a cover crop mixture at the corn V5 growth stage might permit reduced corn planting rates by suppressing weeds and thereby reducing the need for a highly competitive crop. In winter wheat grown with a white clover living mulch, Hiltbrunner et al. (2007b) found that grain yield increased with wheat seeding density. Researching the same species, Thorsted et al. (2006a) showed that increasing wheat row width and the width of rototilled strips in the clover increased wheat grain yield, whereas increasing wheat density had no effect on grain yield. Future research on crop planting pattern and density in living mulch systems might consider a factorial design varying both crop density and mulch density (Wiles et al. 1989). Future research should also place a greater emphasis on balancing the living-mulch-related consequences of planting decisions against other constraints, such as seed cost.

Nutrient Inputs and Irrigation

Because most living mulches have low-growing habits, mulch-crop competition is often most intense with respect to belowground resources (Hartwig and Ammon 2002). Increasing the availability of belowground resources may therefore decrease competition intensity and the severity of yield reductions due to living mulches (Figure 1C). Because nonlegume living mulches often reduce the availability of nitrogen to the main crop (Breland 1996; Feil et al. 1997; Garibay et al. 1997), it may be useful to increase fertilizer nitrogen. Brainard et al. (2004) found that increases in cabbage yield due to supplemental nitrogen tended to be greatest when non-cabbage (living mulch and weed) biomass was high. However, nitrogen addition also tended to increase weed biomass, sometimes by several times. Robertson et al. (1976) reported that a grass living mulch competed with corn for nitrogen. Legg et al. (1979) concluded that maximizing the total dry matter of corn grown in chemically suppressed smooth bromegrass (*Bromus inermis* Leyss.) in a dry year in West Virginia, USA, could require as much as twice the nitrogen rate required for conventionally tilled corn.

The literature on legume living mulches and nitrogen availability is somewhat contradictory. Despite their ability to fix nitrogen, legume living mulches can cause main crop yield losses due to competition for nitrogen (Kurtz et al. 1947, 1952). However, some studies have demonstrated that legume living mulches may instead reduce fertilizer nitrogen requirements relative to the standard for a crop in monoculture. This desirable outcome is more likely if the legume is partially killed, because fixed nitrogen is released from legume tissues only after their death (Alexander et al. 2019b; Jones 1992; Zemenchik et al. 2000). Another strategy involves

intercropping frost-sensitive legumes with winter crops. After functioning as living mulches in the autumn, the legumes are killed by winter temperatures and release their fixed nitrogen to be used by the main crops (Lorin et al. 2016). Nitrogen inputs from a legume living mulch are likely to increase if the legume is present for multiple years (Jones and Clements 1993; Paine et al. 1995; White and Scott 1991). Alexander et al. (2019a) reported that corn planted into kura clover previously managed as forage in Minnesota, USA, did not require fertilizer nitrogen. In a second year of corn planting, fertilizer requirements were similar to those for corn following soybean. Kura clover has also been used to demonstrate that living mulches can decrease nitrate leaching at multiple fertility levels (Ochsner et al. 2010). However, in Iowa, Sawyer et al. (2010) found that a living mulch of kura clover reduced neither the corn's need for fertilizer nitrogen nor the presence of nitrates in the soil profile. Reduced yield responses to added inorganic nitrogen have also been observed in corn and wheat grown with other legumes (Bergkvist 2003b; Hartwig 1989; Radicetti et al. 2018; Wall et al. 1991), although it is worth noting that reduced yield responses to nitrogen can reflect water shortages rather than nitrogen contributions from the mulch (Mayer and Hartwig 1986). The fertilizer equivalency of a legume living mulch declines with increasing mulch suppression and increasing nitrogen fertilization (Duiker and Hartwig 2004). Legumes are most likely to have a positive effect on nitrogen availability in the absence of additional fertilizer (Triplett 1962). In many legume living mulch systems, further work is needed to develop management strategies that achieve high main crop yields with low nitrogen fertilizer inputs.

Adding inorganic nitrogen alters the competitive relationships among crops, living mulches, and weeds. De Haan et al. (1997) found that fertilizer nitrogen decreased corn yield losses due to competition with interseeded medics in Minnesota; however, fertilizer nitrogen also decreased the medics' ability to suppress weeds. Increasing nitrogen may reduce the productivity and competitiveness of legume living mulches relative to nonlegume main crops (Kosinski et al. 2011; Pearson et al. 2014; White and Scott 1991), potentially diminishing the ability of the living mulches to provide benefits such as nitrogen fixation and weed suppression. High rates of nitrogen may also benefit the main crop more than a grass mulch, thus suppressing the mulch (Welch et al. 1967; Wilkinson et al. 1987).

Organic fertility amendments have been evaluated in some living mulch systems. Carreker et al. (1973) tested four rates of poultry litter against a treatment that included no poultry litter but an increased rate of inorganic nitrogen (all treatments included some inorganic nitrogen) in Georgia, USA. They found that corn in live tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort.] had better yields with an intermediate rate of poultry litter than with low or high rates or the entirely inorganic treatment. In organic systems, fertility amendments often improve main crop yield and quality in living mulch treatments as well as treatments without living mulch (Deguchi et al. 2015; Fracchiolla et al. 2020; Montemurro et al. 2017). Antichi et al. (2019) tested a low-input organic system in Italy, including both a red clover (*Trifolium pratense* L.) living mulch and a mixed-species dead mulch over a rotation of savoy cabbage, spring lettuce (*Lactuca sativa* L.), fennel (*Foeniculum vulgare* Mill.), and summer lettuce. The mulches did not compensate for reduced fertility inputs in this system. These findings suggest that living mulches may not eliminate the need for fertility amendments in organic production.

Organic fertility amendments may have different effects on different species. Hiltbrunner et al. (2007a) found that the changes in legume and weed biomass due to the application of liquid farmyard manure were not significant, but manure application resulted in increased winter wheat biomass and grain yield. In cauliflower with a burr medic (*Medicago polymorpha* L.) living mulch, Canali et al. (2015) observed no significant effect of fertility treatment (unfertilized control or organic fertilizers based on dried animal manure, wine distillery wastewater, or municipal solid organic wastes) on crop yield, living mulch biomass, or weed biomass across 2 yr. However, Diacono et al. (2017) found that fertility treatment (unfertilized control or organic fertilizers based on dried animal manure, cattle slurry, or municipal solid organic wastes) did have a significant main effect on yield in cauliflower and tomato. They also observed a significant interaction between fertilization and living mulch treatment (presence and sowing time) on cauliflower yield. Research on fertility amendments in living mulch systems should continue to investigate changes to the relative competitiveness of main crop, living mulch, and weed species.

Living mulches affect the availability of nutrients other than nitrogen, but these dynamics have received less attention. Evidence of potassium deficiency has been reported in corn grown with alfalfa, red clover, or white clover (Deguchi et al. 2010; Jellum and Kuo 1990). In contrast, white clover has been reported to increase phosphorous uptake in corn by promoting colonization by arbuscular mycorrhizal fungi (AMF; Deguchi et al. 2005, 2007, 2012, 2017). A similar AMF effect apparently occurred in one of two artichoke (*Cynara cardunculus* L.) cultivars grown with a mixed-species living mulch (Trinchera et al. 2016).

Like competition for nutrients, competition for water is an important mechanism by which a living mulch may reduce crop yield (Hartwig and Ammon 2002; Kurtz et al. 1952). Where economically feasible, irrigation may reduce competition intensity. For example, Carreker et al. (1972) found that corn planted in unsuppressed tall fescue was largely killed by summer droughts in Georgia, USA. More corn survived if the tall fescue was suppressed with herbicides and/or irrigation was provided. Similarly, Adams et al. (1970) reported that irrigation protected corn grain yields from severe losses due to competition with chemically suppressed living mulches of tall fescue and coastal bermudagrass [*Cynodon dactylon* (L.) Pers.] in a year with low rainfall. In cabbage grown in Oregon, Graham and Crabtree (1987) suggested that yield reductions associated with a living mulch of perennial ryegrass (*Lolium perenne* L.) were primarily due to competition for water and could be mostly avoided by irrigation and chemical suppression of the mulch. Irrigation may be less effective when living mulch water uptake does not restrict crop yield. Box et al. (1980) found that irrigation increased corn stalk and grain yield in Georgia, but the effects of irrigation were similar between living and dead mulch treatments. They concluded that the negative effect of the living mulch on yield must result from factors other than competition for water.

Mechanical Management

Mechanical or chemical management of living mulches can serve several purposes. It is often necessary to kill strips of a pre-established ground cover to permit main crop planting and establishment. Management practices can also decrease the severity of mulch-crop competition and/or provide supplemental weed control (Figure 1D). In early studies on living mulches, herbicides were often considered essential (Teasdale 1996). However,

trends toward herbicide rate reduction and organic farming have increased the demand for mechanical management strategies (see the Supplementary Table). These strategies are often effective but may not kill weeds occurring in crop rows or gaps in living mulch stands. In weedy situations, the presence of living mulches sometimes complicates weed suppression by limiting the number of available mechanical tools (e.g., eliminating in-season cultivation options). For this reason, it is desirable to plant competitive main crops and living mulches. Competitive living mulches typically require management to reduce mulch-crop competition.

Strip tillage can be an effective means of suppressing living mulches. In a factorial study of living mulch species, tillage, and herbicide treatments, Wiggans et al. (2012) found that corn grain yield losses could be prevented if Kentucky bluegrass was strip-tilled in the fall, then treated with paraquat (0.84 kg ai ha^{-1} over the entire plot) and 25-cm bands of glyphosate (1.0 kg ai ha^{-1}, applied twice over the row) around planting time. This result echoed an earlier suggestion that mechanical and chemical methods should be combined for row establishment in a mixed-species living mulch (Martin et al. 1999). When only one method is used, strip tillage sometimes outperforms chemical treatments. Adams et al. (1970) found that strip tillage could be a better method for suppressing coastal bermudagrass than a growth retardant, maleic hydrazide (4.5 or 9 kg ha^{-1}), which also delayed corn development. More recently, Pearson et al. (2014) reported that strip tillage of well-established kura clover shortly before corn planting resulted in higher corn yields than herbicide bands in one of two years. Ginakes et al. (2018) compared glyphosate banding (4 kg ae ha^{-1}, 30-cm bands), shank tillage (traditional strip till unit), zone tillage (rotary zone tiller with power take-off), and shank plus zone tillage as methods of establishing corn in kura clover. Relative to the herbicide bands, shank plus zone tillage resulted in reduced kura clover encroachment into the crop rows and higher nitrogen availability (see also Alexander et al. 2019b on strip tillage and nitrogen availability). In another study of corn grown in a kura clover living mulch, Dobbratz et al. (2019) observed a yield advantage of zone tillage over shank tillage or herbicides in one of two years. Hooks et al. (2013) reported that eggplant (*Solanum melongena* L.) yield was reduced when the crop was transplanted into a mowed red clover stand (first year), but there was little yield reduction when the red clover was instead strip-tilled (second year).

Although tillage can be a powerful tool for reducing mulch-crop competition, main crop yield does not always increase with increased soil disturbance. Beale and Langdale (1964) compared tillage treatments that disturbed 100% (turnplow), 50% (rip plant), or 33% (lister plant) of an established coastal bermudagrass sod in advance of corn planting. Corn yields were similar between treatments and postharvest grass stands were improved by less aggressive tillage. Hartwig and Loughran (1989) found that a crownvetch living mulch had little effect on either corn or summer annual weeds, regardless of tillage treatment (no-till or primary tillage with a moldboard plow, heavy offset disk, or chisel plow, followed by secondary tillage with a tandem disk). In sweet corn, Mohler (1991) found that strip tillage of a white clover living mulch did not increase marketable ear weight relative to a no-till treatment.

Living mulches may be suppressed with mechanical tactics other than preplant tillage. In white cabbage, Brandsæter et al. (1998) found that mowing did not reduce yield losses due to competition with living mulches of subterranean clover or white clover. However, these yield losses were reduced by rototilling between the rows 6 wk after transplanting. Rototillage also improved weed suppression. Similarly, Grubinger and Minotti (1990) reported that

white clover suppression by partial rototilling resulted in higher corn yields than mowing in the clover establishment year. Chase and Mbuya (2008) found that mowing living mulches failed to improve yield in broccoli. Graham and Crabtree (1987) and Vrabel et al. (1981) reported that mowing was often inferior to chemical control for living mulch suppression. In zucchini (*Cucurbita pepo* L.) grown with a living mulch of sunnhemp (*Crotalaria juncea* L.), yield losses were reduced when the living mulch was cut to a height of 20 cm rather than 45 cm (Hinds et al. 2016). Mechanical control of living mulches could also be improved by the introduction of novel methods. Båth et al. (2008) were able to increase the aboveground biomass of white cabbage by pruning the roots of living mulches (custom equipment with horizontal blades at 0.2 m depth). The increase in cabbage biomass was most dramatic with a living mulch of winter rye, sown shortly before cabbage planting, but it was also significant with red clover, birdsfoot trefoil, and salad burnet (*Sanguisorba minor* Scop.), all sown in the year prior to the experiment.

Mechanical practices may improve crop nitrogen uptake. Thorsted et al. (2006b) used a weed brusher on a white clover living mulch (cut at the soil surface in 11-cm bands between crop rows) and left cut material on the ground to release nitrogen. This brushing method increased wheat nitrogen uptake and grain yield relative to an unbrushed control. Another strategy intended to increase nitrogen availability to the crop involves depositing legume clippings onto the crop row after mowing. It is not clear that this strategy is effective (Thériault et al. 2009), but removing clippings from the system could have a negative effect. In a study of soil nitrogen beneath an alfalfa sod, Varco et al. (1991) found that nitrogen levels at 0 to 10 cm were lower in a cut-and-remove treatment than in a cut-and-return treatment after 14 d.

Future research on the mechanical management of living mulches may uncover strategies that balance soil fertility, weed control, and crop yield without much soil disturbance or damage to the living mulches. For now, the most reliable methods of reducing competition against main crops are fairly intense (e.g., strip tillage rather than mowing) or combine mechanical control with other approaches, such as chemical control.

Chemical Management

Like mechanical control, chemical control may promote several goals in living mulch systems, including better crop establishment, less mulch-crop competition, and greater weed suppression. At the same time, living mulches are valued for their potential to facilitate herbicide rate reductions (Moore et al. 2019; Norsworthy et al. 2012). Herbicide rate reductions are desirable for environmental reasons and may promote long-term sod persistence, but herbicides applied at reduced rates may not adequately reduce competition against the main crop (Bennett et al. 1976; Buck 2018; Kosinski et al. 2011; Williams and Hayes 1991). In contrast, herbicide use at high rates tends to reduce mulch-crop competition at the expense of ground cover, biomass accumulation, and weed suppression by the living mulch. Early research on living mulches sometimes failed to identify herbicide treatments that achieved good main crop yields without killing the living mulches or severely reducing ground cover (Hughes and Sweet 1979; Linscott and Hagin 1975). Subsequent research has focused on developing treatment programs that protect yields without excessive mulch kill. These goals may require herbicide choice, rate, application method, and/or timing to be tailored to the living mulch system (Supplementary Table).

One way to manage the tradeoff between protecting the main crop and maintaining the living mulch focuses on spatial variation in herbicide applications. For instance, using herbicides to kill strips of a living mulch prior to crop planting or emergence can decrease interspecific competition. Zemenchik et al. (2000) found that killing 61-cm bands of kura clover with glyphosate (4.0 kg ae ha^{-1}) and postemergence dicamba (0.7 kg ae ha^{-1}) resulted in improved corn yields in one of two years over a treatment with glyphosate (1.7 kg ae ha^{-1}) and postemergence bromoxynil (0.4 kg ai ha^{-1}) applied to the entire field. In contrast, Eberlein et al. (1992) reported that unirrigated corn yields were sometimes greater with broadcast applications of atrazine (1.68 kg ha^{-1}) than with band applications (3.36 kg ha^{-1}, 38 cm) in an alfalfa living mulch. This difference was not observed in an irrigated treatment. Strip width may influence the efficacy of band applications. Kumwenda et al. (1993) demonstrated that killing crimson clover (*Trifolium incarnatum* L.) in strips covering 60% to 80% of total field area could prevent corn yield losses while still allowing clover reseeding. Similarly, Wilkinson et al. (1987) increased corn yields by doubling the width of a killed strip of tall fescue (0.20 m to 0.41 m). It is also possible to use band applications after main crop emergence. Reddy and Koger (2004) found little difference in yield between corn planted into a live hairy vetch and corn planted into 38-cm bands killed with paraquat (1.1 kg ai ha^{-1}). However, postemergence applications of glyphosate (0.84 kg ae ha^{-1}) were more effective when broadcast than applied in 38-cm bands over the row, partially because the broadcast treatment contributed more to weed control.

Weed suppression can be improved by selecting appropriate herbicides and considering their interactions with other management decisions. In a study of both cultural and chemical factors, Rajalahti et al. (1999) reported that interseeding living mulches 3 wk after planting could facilitate a 70% reduction in herbicide use in potato (*Solanum tuberosum* L.). Nurse et al. (2018) tested three living mulches in sweet corn, both independently and matched with herbicides appropriate for grass control: adzuki bean [*Vigna angularis* (Willd.) Ohwi & H. Ohashi] with linuron plus *S*-metolachlor (0.55 plus 1.14 kg ai ha^{-1}), cereal rye with saflufenacil (0.075 kg ai ha^{-1}), and oilseed radish (*Raphanus sativus* L.) with pendimethalin (1.68 kg ai ha^{-1}). Adzuki bean provided poor grass control in the absence of herbicides, but the combination of adzuki bean, linuron, and *S*-metolachlor was highly effective. In many cases, the weed control achieved by living mulches depends on the identity of problem weeds. Lightly to moderately suppressed crownvetch improved control of dandelion (*Taraxacum officinale* F.H. Wigg.) and yellow nutsedge (*Cyperus esculentus* L.) in corn but was not helpful in controlling redroot pigweed (*Amaranthus retroflexus* L.; Hartwig 1977, 1989; Hartwig and Loughran 1989).

A different approach to weed suppression involves planting herbicide-resistant crops. In an early test of this strategy, Affeldt et al. (2004) found that glyphosate- or glufosinate-resistant corn could be grown in a kura clover living mulch. The kura clover did not reduce yield relative to monocrop corn when it was suppressed with a preplant application of glyphosate plus dicamba (1.66 plus 0.14 kg ae ha^{-1}) and postplant banding of dicamba plus clopyralid (0.56 plus 0.05 kg ae ha^{-1}, 25 cm) before the in-season application of glyphosate (0.83 kg ae ha^{-1}) or glufosinate (0.37 kg ae ha^{-1}) between the corn V3 and V5 stages. In contrast to the more standard practice of using glyphosate to terminate a living cover crop by the time of main crop emergence (Petersen and Röver 2005), this system allows significant kura clover regrowth. It has increased in popularity since the study published

by Affeldt et al. (2004). However, it is also worth noting that living mulches can be managed with chemical treatments other than popular herbicides. For example, Elkins et al. (1979) tested several growth retardants [fluoridamid (4.5 to 9 kg ha^{-1}), maleic hydrazide (4.5 to 9 kg ha^{-1}), and mefluidide (0.6 to 1.1 kg ha^{-1})] or herbicide treatments [dalapon (2.2 to 4.5 kg ha^{-1}), glyphosate (1.1 to 2.2 kg ha^{-1}), glyphosate plus atrazine (1.7 to 2.2 plus 1.1 kg ha^{-1}), metolachlor (4.5 to 9 kg ha^{-1}), metolachlor plus atrazine (6.7 to 9 plus 0.6 to 1.1 kg ha^{-1}), and paraquat plus atrazine (0.6 to 1.1 plus 1.1 kg ha^{-1})] on a tall fescue or Kentucky bluegrass sod for corn. With the exception of paraquat plus atrazine, which largely killed the forage grasses, most growth retardants or herbicides achieved some success in promoting good corn yields while maintaining sufficient ground cover to prevent erosion.

Application timing and method account for considerable variation in herbicide efficacy. Bergkvist (2003c) tested various rates of isoproturon plus diflufenican in a third consecutive crop of winter wheat sown in a white clover living mulch. All autumn applications (0.375 to 1.625 plus 0.075 to 0.15 kg ha^{-1}) were effective in reducing annual weed biomass and increasing wheat grain yield without permanently damaging the living mulch, whereas a spring application of isoproturon only (1.25 kg ha^{-1}) reduced white clover biomass and ground cover without effectively suppressing weeds or increasing yield. Within the spring season, Cardina and Hartwig (1980) found that preemergence applications could be superior to preplant incorporated applications for control of a crownvetch living mulch in corn, likely because the preplant incorporated applications occurred before the crownvetch began spring growth. Their results agree with other suggestions that living mulches should be treated while actively growing (Rinehold 1987) and that crownvetch is a good target for chemical manipulation (Hartwig and Hoffman 1975; Hartwig 1976). Teasdale (1993) showed that the weed control benefit of hairy vetch was greatest early in the corn season and suggested that this living mulch could contribute to a weed control program including only postemergence herbicides.

Future Directions

Given the pressing needs to diversify weed control programs, limit land degradation, and address environmental issues associated with intensive farming (Godfray et al. 2010; Mortensen et al. 2012), we believe that living mulches merit increased attention. Living mulches are particularly appropriate for growers willing to accept minor yield losses in exchange for ecosystem services. More than 50 yr of research on living mulches have revealed that cultural, mechanical, and chemical management practices can increase main crop yields and promote services such as weed control. Best management practices vary across living mulch systems, so further research is needed to develop system-specific recommendations. General research priorities include refining the list of effective living mulch species, improving the options available for organic systems, identifying low-input chemical control strategies, and adopting a more holistic approach to living mulch management.

Candidate living mulches have been selected from the enormous diversity of species and cultivars used as classic (terminated) cover crops and forages. Most of this diversity remains unexplored in the context of living mulch systems. However, the ideal living mulch would meet criteria not always required of other cover crops, such as complementarity with main crop species. Therefore, the widespread commercial use of living

mulches may be facilitated by breeding programs (Moore et al. 2019) following the living mulch ideotypes that have already been proposed (Buhler et al. 1998; De Haan et al. 1994; Flynn et al. 2013). Another strategy involves the introduction of living mulch species to different regions. Radicetti et al. (2018) observed that intercropped subterranean clover reduced wheat yields in temperate agroenvironmental zones (Mediterranean North and Continental) but caused little yield reduction under colder temperatures (Atlantic North) or drier conditions (Mediterranean South). On a larger scale, (sub)tropical species may offer management advantages as temperate living mulches because the onset of cool temperatures could automatically terminate growth and prevent seed set. Bhaskar et al. (2020) tested two (sub)tropical species, sesbania [*Sesbania sesban* (L.) Merr.] and sunnhemp, as living mulches for fresh-market field tomato in New York, USA. Although sesbania did not successfully establish, the sunnhemp results were promising: sunnhemp established and grew well until growth was arrested by tomato harvesting and cool fall temperatures. In addition to being easier to terminate, non-native species are less likely to suffer from or carry native pests and pathogens. Despite these possible benefits, species introductions involve risks that should be evaluated on a case-by-case basis. Notably, introduced living mulch species might become invasive weeds, although this outcome is less likely for species that cannot set seed in the introduced range. Lastly, living mulches have been considered as components of agroecological strategies to mitigate the effects of climate change (Diacono et al. 2017), a goal that might require the identification of living mulches with broader climatic requirements.

Because herbicides are among the most effective tools for living mulch management, incorporating living mulches into organic systems may require additional planning. Such planning is often worthwhile: living mulches make valuable contributions to weed management, soil health, and other aspects of sustainability in organic systems (Leary and DeFrank 2000; Montemurro et al. 2020; Vincent-Caboud et al. 2017). In organic systems (even more than non-organic ones), it is prudent to use cultural methods to maximize the main crop's competitiveness relative to the living mulch rather than relying exclusively on mechanical control. Such methods may include identifying highly competitive crop cultivars and less competitive living mulches (including annuals) or adjusting relative planting times and densities. Fertility amendments can also modify competitive dynamics. Mechanical management programs for organic systems might involve preseason strip tillage, in-season rototilling, and/or mowing to short heights.

Chemical control provides additional options but can be challenging to implement. A single, high-rate herbicide application often eliminates the benefits of a living mulch, whereas low-rate applications tend to allow excessive mulch-crop competition. Improved control of living mulches and weeds may come from herbicide combinations, which have been common practice from the outset of living mulch research (Cardina and Hartwig 1980; Elkins et al. 1979, 1982, 1983; Hartwig 1977; Linscott and Hagin 1975). Repeated herbicide applications have also been evaluated. For instance, Pedersen et al. (2009) found an increase (generally insignificant) in soybean yield with more glyphosate applications over a kura clover living mulch. Some recent work has focused on combining these two strategies. In the study of tomato grown with a sunnhemp living mulch (Bhaskar et al. 2020) and a concurrent study of sunnhemp in monoculture (Bhaskar et al. 2021), two herbicides were applied sequentially at reduced rates. Applying a herbicide with soil residual activity followed by a herbicide with greater postemergence activity helped balance living mulch performance, weed control, and (in Bhaskar et al. 2020) tomato yield. Both reduced-rate applications included surfactants, which increased the postemergence injury caused by (primarily preemergence) residual herbicides. These findings demonstrate the potential for improved application techniques to enable herbicide rate reductions. Further research must evaluate how chemical control practices interact with decisions about planting and mechanical control.

Taken as a whole, the literature on living mulches suggests that high-precision, multipronged management approaches are most likely to result in good weed control and yield outcomes. Ideally, many aspects of cropping system management would contribute to competitive environments in which living mulches promote weed suppression without outcompeting main crops. The design of integrated management programs should reflect a long-term perspective. For example, weed suppression is relevant not only to main crop yield, but also to weed seed production. Living mulches can reduce weed seed production more effectively than cover crop residues (Teasdale et al. 2007). However, living mulches are unlikely to completely prevent weed seed production, especially if they are strongly suppressed to reduce mulch-crop competition. Management practices that kill weeds while providing milder living mulch suppression could limit additions to weed seedbanks. Trends in weed seed production and seedbanks have been studied less frequently than trends in end-of-season weed biomass (but see Brainard and Bellinder 2004; Gibson et al. 2011; Uchino et al. 2009) and represent an important area for future studies.

Weed control and main crop yield can vary widely in living mulch systems. Other benefits and drawbacks of these systems, such as long-term impacts on soil health or arthropod communities, are harder to observe. Management practices that influence one aspect of cropping system function can also influence other aspects. For all these reasons, it is difficult to determine when and how living mulches should be adopted. These knowledge gaps can be reduced by research projects that adopt standard practices and holistic, long-term perspectives. Specifically, we suggest that future experiments seek to accomplish one or more of the following goals:

1. Provide a point of reference to the existing literature. For example, information on a novel management regime for a novel living mulch–main crop combination is easier to interpret if the management regime is also applied to a previously characterized combination.
2. Apply management factors with at least three levels to living mulch, nonliving mulch, and no mulch plots. Avoid confounding the effects of living mulches with the effects of tillage.
3. Report data on additional factors (e.g., soil characteristics or pest suppression) alongside standard measurements such as living mulch biomass, weed biomass, and main crop yield. Data on (financial) costs of living mulch establishment and maintenance are also valuable.
4. Collect multiyear datasets in perennial systems. In annual systems intended as components of rotations, test for rotation effects.

Research following these guidelines could form the foundation for more quantitative cost-benefit analyses. A long-term goal should be the creation of data-driven decision-support tools

identifying key challenges and opportunities associated with living mulches.

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