TECHNICAL PAPER

Working Party 2.08.04

Mini-review of cover crop potential for weed management in agroforestry systems

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Abstract

Weed management is an integral practice for agriculture-, horticulture-, and forestry-related plant production systems. Weeds create similar problems in improved agroforestry cropping systems as in conventional agriculture and horticulture. While traditional chemical and mechanical weed management techniques are effective for these practices, they require a great deal of labor, are very costly, and can be detrimental to soil health and water quality.

An alternative to traditional weed management techniques is the use of ground cover, known as cover crops, to control the spread and suppress the development of weed species. Cover cropping is a sustainable weed management practice that has great potential for weed suppression through competitive inhibition and allelopathic interactions.

Our objective was to evaluate the potential of cover crops as an effective management tool for suppression of weed competition in agroforestry systems. In this context, we review the five major agroforestry practices recognized today. Additionally, we discuss traditional weed management techniques and their limitations to further understand the need for cover crops as an alternative mode of weed suppression. Lastly, we explore cover crop weed management techniques and highlight cover crop species that have the greatest potential for use in agroforestry systems.

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1. Introduction

Weeds are a unique group of plant species; their ability to overrun and thrive on disturbed landscapes makes them difficult to eradicate and manage (Buhler et al., 1998). These opportunistic species cause economic losses by reducing crop quality and yields. Worldwide, weeds cause yield losses of around 34% among the major crops planted, which is higher than losses caused by other pests (Jabran et al., 2015). Weed management is a vital element of agricultural systems. Since weeds coincide spatially with crops, they deprive crop plants of nutrients, water, and light, and produce allelochemicals that hinder crop growth (Alley et al., 1999; Jabran et al., 2015; Sturm et al., 2018). Weeds are most competitive with crops that are at early growth stages; therefore, a weed management strategy that ensures early season weed suppression can be crucial for crop growth, development, and yield (Osipitan et al., 2018). Conventional weed management is typically accomplished by means of chemical, mechanical, or physical suppression. While these methods of weed management are proven, these techniques can be costly and laborious, and can (or, often) degrade soil health and cause soil erosion (Van Sambeek and Rietveld, 1982). Weeds are a major impediment to the development of improved cropping systems, which is especially true for agroforestry systems, in which crops are intentionally combined with trees and/or livestock.

Ground cover, more specifically cover crops, can be used to suppress and manage weed competition. This alternative weed management technique has the potential to be used in agroforestry tree–crop systems. Cover crops offer a sustainable method of weed suppression, soil protection, and nutrient provisioning for optimal plant growth (Alley et al., 1998). Generally, there are two ways that cover crops are implemented for weed management. The first way is to use cover crops as “living mulches,” wherein the cover crops are planted to interfere with the growth of surrounding weeds through competition for water, nutrients, and light. The second method is to terminate the cover crops and utilize their biomass/residues to suppress weed growth (Weston, 1996). Furthermore, a number of cover crops produce allelopathic growth inhibitors that affect nearby plants. These allelopathic inhibitors are troublesome in certain situations, but, under appropriate conditions, are effective in suppressing weed seedlings (Weston, 1996). Proper cover crop selection is thus essential in order to minimize competition with desired trees and/or crops for water and nutrients, and account for allelopathic effects.

Weeds exist across the spectrum of plant production systems because of the unique niche created via disturbance (Buhler et al., 1998). Further, weeds hinder the development of improved cropping systems such as agroforestry systems. Weed management is integral to the overall success of these systems, especially when traditional management techniques have been exhausted, or have become too costly. Certain cover crops have the potential to selectively inhibit the growth of weed species (Weston, 1996) and provide an opportunity for improved growth and survival of target crops and trees.

Our objective was to evaluate the potential of cover crops as an effective management tool for the suppression of weed competition in agroforestry systems. In this context, we review the five major agroforestry practices recognized today (**Figure 1**). Additionally, we discuss traditional weed management techniques and their limitations in order to further understand the need for cover crops as an alternative mode of weed suppression. Lastly, we explore cover crop weed management techniques and highlight cover crop species that have the greatest potential for use in agroforestry systems.

Figure 1. Five major agroforestry practices utilized in temperate climates. Source: USDA Forest Service, National Agroforestry Center (https://www.fs.usda.gov/nac/practices/index.shtml).

2. Agroforestry Practices

Alley cropping

Alley cropping (also referred to as intercropping) is the intentional combination of trees and crops in which two or more sets of single or multiple rows of trees/shrubs are established at wide spacing, thus creating “alleys” where agricultural, forage, and horticultural crops are planted (Walter et al., 2018). Alley cropping provides an alternative revenue stream from tree products (e.g., wood, nuts, and fruits), as well as additional benefits such as erosion reduction, improved water quality, crop protection, livestock protection, and diversification of farm enterprises. With this being said, there are limitations to alley cropping, including, but not limited to: intensive management and upkeep, removal of land from crop production, lack of available markets, and competition for light and nutrients among crops and trees (Walter et al., 2018).

Forest farming

The intentional combination of non-timber forest products (NTFPs) in forested areas is referred to as forest farming (Munsell et al., 2018). Though forest farming is commonly practiced on smaller scales, systems often contain great species diversity (Mudge and Gabriel, 2014). Within forest farming systems, interactions between trees and understory crops are monitored, with long-term forest health and productivity in mind (Munsell et al., 2018). There are four categories of NTFPs: medicinal, edible, floral, and decorative/craft. Forest farming allows for alternative income opportunities, while creating diverse farmsteads. Market opportunities for forest farming can be lucrative, given that they are available and stable.

Silvopasture

The intentional combination of trees, livestock, and forage (pasture) is referred to as silvopasture (Sharrow et al., 2009). There are two approaches in silvopasture: 1) the establishment of trees into existing forage or pasture, and 2) the establishment of forage into managed forests. Grazing livestock in wooded areas without the presence of forage/pasture is not silvopasture, which is a common misconception. Intensive management and careful selection of trees and forage are vital in the adoption of silvopasture; trees, livestock, and forage all compete for essential nutrients, light, and water. In general, benefits of silvopasture include reduced livestock stress, improved nutrient cycling and plant diversity, and enhanced wildlife habitat. The introduction of livestock to forage and young tree plantings can be a limiting factor, and therefore, managed intensive grazing (MIG) is needed in pasture areas, as well as protection of young trees that are susceptible to livestock grazing and trampling (Walter, 2018).

Upland and riparian forest buffers

Pollution from agricultural runoff is a major problem facing many of the world's waterways today (Lin et al., 2004; Rosa et al., 2017; Zhu et al., 2020). Several methods have been implemented to reduce the amount of runoff entering these waterbodies. Of these, upland and riparian forest buffers are sustainable agroforestry practices for agricultural pollution mitigation. Upland buffers are narrow strips of trees, shrubs, grasses, and forbs that are planted on the upland contours of watersheds within agricultural fields and serve as barriers for non-point source pollution that could eventually make its way to nearby watersheds (Schultz et al., 2018).

A similar concept with additional benefits, riparian buffers are planned combinations of trees, shrubs, grasses, and forbs adjacent to streams (Garrett, 2005). Riparian buffers remove sediments, nutrients, organic matter, pesticides, and other pollutants from surface runoff and groundwater via deposition, absorption, plant uptake, denitrification, and other processes (Schultz et al., 1995; Volk et al., 2006). In addition, riparian buffer root systems help stabilize soils and prevent erosion from stream movement and periodic flooding (Isebrands, 2014; Tufekcioglu et al., 2003). Riparian buffers thereby reduce pollution and protect surface and subsurface water quality while enhancing water body ecosystems (Schultz et al., 2004).

Riparian forest buffers are typically composed of three zones, as explained by Schultz et al. (2018). Zone 1, the zone closest to the stream, is composed of fast-growing grasses, shrubs, or trees that help to stabilize stream banks and can tolerate periods of flooding. The primary purpose of zone 2, the middle and widest zone, is provisioning nutrient uptake and enhanced water quality. This zone must be able to tolerate periodic flooding. Zone 3 is the area nearest to agricultural fields and helps to trap nutrients and sediment and disperse runoff. This zone is usually comprised of grasses and forbs that have stiff stems. This combination of grasses, shrubs, and woody species maximizes the above- and below-ground structures of multiple species to create an agroforestry system that provides runoff reduction as well as wildlife habitat and biomass feedstocks (Schultz et al., 1995). Flooding is one of the challenges associated with riparian buffers and is often addressed through species selection. Poplars (*Populus* spp.), willows (*Salix* spp.), and their hybrids are ideal for riparian buffer applications due to their tolerance of inundation and elevated evapotranspiration rates (Isebrands et al., 2014).

Windbreaks

Windbreaks are tall, dense, continuous walls of vegetation that change wind flow patterns by intercepting wind as it passes through (Anderson et al., 2003). Windbreaks are commonly used to protect crops and livestock, reduce erosion, prevent herbicide and pesticide drift, control drifting snow, improve and/or create wildlife habitat, and reduce odor and noise (Heavey and Volk 2014; Isebrands et al., 2014; Kuzovkina and Quigley, 2005). The longer and wider a windbreak is, the larger the protected area it provides on the leeward (downwind) side. A desirable windbreak can aid in the reduction of wind speeds by 35 to 95%, depending on the distance from the windbreak (Ucar and Hall, 2001). To have a significant effect, windbreaks must be at least 3.28 meters or higher, consisting of trees, shrubs, tall perennials, or annual plants that will attain a sufficient height to reduce the wind speeds (Wight and Straight, 2018). Two primary variables that windbreaks control are temperature and wind speed (Bentrup et al., 2019). Configuration and species selection are necessary because not all species and configurations will be effective (Lin et al., 2009). Windbreaks offer a plethora of benefits, but the removal of land from crop production, intensive management, and low financial returns are seen as disadvantages, which ultimately hinder the implementation of these systems.

3. Traditional Weed Management Techniques

Mechanical Control

Mechanical control involves the above- or below-ground cutting, uprooting, and burial of competing weeds (i.e., mowing, scalping, hoeing, or tilling) (Van Sambeek and Garrett, 2004). Many mechanical implements have been developed for agricultural uses, and these implements are often used in site preparation, as well as site management (Dickmann and Stuart, 1983). While mechanical control is one of the more effective ways to manage weeds and ground vegetation, it has a number of potential disadvantages for erosion, soil health, and cost (Van Sambeek and Garrett, 2004). Erosion occurs most rapidly on agricultural or disturbed lands when there is no vegetation cover to slow surface runoff or allow infiltration (Curran et al., 2006; De Baets et al., 2011). Cultivated crop fields that are weed free may be aesthetically desirable, but aid in erosion and denitrification of key nutrients and organic matter (Akobundu, 1992). Aboveground cover provides needed protection for the soil while helping to stabilize it as well.

Soil health is another ecosystem service that can be diminished when using mechanical control methods. Continued mechanical control of weeds not only increases the vulnerability of land to erosion, but equipment used for mechanical control can also lead to soil compaction and reduced water infiltration (Van Sambeek and Garrett, 2004). These impacts can be detrimental to soil biota and decrease future crop productivity. Other effects of repeated mechanical cultivation of soil include increased breakdown of organic matter, reduced amounts of soil aggregates which are necessary for nutrient retention, and increased temperatures that accelerate nitrogen volatilization (Buhler et al., 1998). With mechanical control of weeds, soil tilth and organic matter can also be dramatically reduced, which in turn leads to decreased soil productivity for any type of crop production system (Curran et al., 2006). The loss of the vital components to soil health through mechanical weed control often leads to degradation of the most fertile upper layers of the topsoil (Van Sambeek and Garrett, 2014).

While mechanical control of weeds is proven to be effective, equipment, labor, and energy (fuel) are expensive and time consuming, comprising the majority of system maintenance input costs (Heller et al., 2003; Lazarus et al., 2015). For agroforestry systems that incorporate trees and crops, specialized equipment is likely required. Oftentimes, this equipment is not marketed nor readily available, and it must be specially fabricated, making such machinery less favorable than that of major cropping systems (Pfeiffer et al., 2015).

Chemical control

Increases in labor and energy costs have made chemical weed control a popular control method in cropping systems (Sondhia, 2014). The use of chemicals for weed suppression allows for quick control of targeted weed species, which makes this control method appealing for farmers with limited time and labor resources. More than 44% of the agriculture community around the world uses herbicides to control weed species (Sondhia, 2014). While an effective option, repeated chemical usage can pose problems to non-target species, soils, water, and human health, as well as lead to herbicide resistance in weeds.

Although chemical control of weed species is very popular, repeated applications increase the risk of affecting non-target species. A large portion of agrochemicals cannot be entirely utilized or taken up by crops (Zhu et al., 2020). This is especially prevalent when chemicals are applied in undesirable weather conditions. Wind can cause chemical drift whereby small droplets or particles containing herbicides are carried to non-target species (e.g., crops, animals, or humans) (Kudsk and Streibig, 2003). This drift can affect the health and survival of nearby non-target plants as well as pollinators that depend on them (Bentrup et al., 2019), which also can negatively impact health of nearby wildlife. To avoid chemical drift, chemical application must be executed in ideal situations: little to no wind is required, rainfall must occur at least 24 hours after application, and chemical application must be applied at recommended doses (Sondhia, 2014).

After chemical application, processes such as volatilization, leaching, runoff and degradation by microbes, chemical processes, and photodecomposition can determine the fate of herbicide in soil (Sondhia, 2014). While the intention of chemical herbicide applications is to eliminate competition for crops, oftentimes residual chemicals are absorbed into the soil where they can remain in their original or closely related phytotoxic form (Sondhia, 2014). These forms present problems for soil health, as residual chemicals break down microbial processes in the soil and allow for potential leaching into the groundwater and nearby surface water (Kudsk and Streibig, 2003). Combined with chemical drift, herbicide runoff and leaching of chemicals into groundwater and nearby surface water pose a risk of non-point source pollution to nearby waterways and watersheds (Lin et al., 2004). This causes great concern for aquatic ecosystems and human health as the level of contamination increases.

In addition to the environmental effects of chemical application, target species can also build up resistance to herbicides after repeated applications (Ashworth et al., 2016; Busi and Powles, 2009; Heap 2013; Manalil et al., 2017). Herbicide resistance often occurs when herbicide application rates are lower than recommended doses, leading to incomplete suppression of target weeds (Manalil et al., 2017), but resistance is possible even after applications using the recommended doses. Due to this evolution of herbicide-resistant weeds, chemical control can become ineffective and require further research to develop alternative herbicides for weed control.

Mulches

Generally, there are two types of ground cover management when using mulches: 1) organic (carbon-based) and 2) inorganic/barrier mulches (Van Sambeek and Garrett, 2004). Organic carbon-based mulches consist of shredded bark, wood chips, grass clippings, and other appropriate materials (Dickmann and Stuart, 1983). The breakdown of organic mulches requires reapplication to remain effective, thus leading to additional material and establishment costs (Van Sambeek and Garrett, 2004). Effective weed management may require at least 5 to 10 cm of mulch, and in certain cases fertilization may be needed to maintain optimal soil pH and fertility (Dickmann and Stuart, 1983). Another concern with organic mulches is the introduction of new weeds, pathogens, and cover provided for pests (Van Sambeek and Garrett, 2004). Inorganic mulches/barriers include manufactured products such as black polyethylene plastic, plastic films, and landscape fabric. These types of barriers offer a one-time installation with little maintenance, but are permanent until removed (Van Sambeek and Garrett, 2004). Material and labor are limiting factors when using this type of mulch. Incorrect anchoring of these manufactured materials can add to the management and upkeep costs of barrier mulches. Barrier mulches can also provide an ideal habitat for pests and protect them from natural predation, thus reducing the benefits of weed management (Van Sambeek and Garrett, 2004). Further, while inorganic/barrier mulches are an effective option, they can be economically and environmentally unattractive (Dickmann and Stuart, 1983). Overall, using mulches for weed control may not be suitable for large-scale operations, but can be a viable option in small-scale settings (Dickmann and Stuart, 1983). Both types of mulches should be able to block sunlight, allow water infiltration, protect soil, reduce evaporation, and biodegrade, and both types are readily available and easy to install (Dickmann and Stuart, 1983). In terms of weed management, the use of mulches is effective, but can be expensive and laborious.

All of the aforementioned traditional weed management techniques (mechanical control, chemical control, mulches) can be effective strategies for controlling weeds. However, rising costs, high upkeep, soil degradation, and human health issues warrant alternative, environmentally friendly methods for weed management. Cover crops are a potential option for natural weed management and are explored in more depth in the following sections.

4. Cover Crop Weed Management Techniques

How cover crops control weeds

'Cover crops' is a general term that incorporates a wide range of plant species that are grown for their ecological benefits in cash crop productions and environmental applications (Teasdale et al., 2007). Cover crops are intentionally established ground cover designed to reduce the amount of resident vegetation and delay normal succession of perennial weeds (**Figure 2**; **Figure 3**) (Van Sambeek and Garrett, 2004). Although annual weeds are also a target for management, perennial weeds tend to be the most serious competitor for agricultural systems because they can be more difficult to control due to their larger nutritional reserves and faster establishment rates (Teasdale et al., 2007). Establishment of cover crops helps to control weeds through competition for light, water, and nutrients (Alley et al., 1998). In addition to outcompeting them, cover crops have the ability to manage weeds by 'smothering' them with terminated plant residue, or by producing allelopathic growth inhibitors (Weston, 1996).

Figure 2. White clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), and meadow fescue (*Festuca pratensis* Huds.) cover crop mix for weed management. Photo by Brent S. DeBauche, Center for Agroforestry, University of Missouri – Columbia.

Figure 2. White clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), meadow fescue (*Festuca pratensis* Huds.), spring oats (*Avena sativa* L.), and brassicas (*Cruciferae* family) for weed management in poplar (*Populus* L. spp.) and willow (*Salix* L. spp.) cutting orchards. Photos by Brent S. DeBauche, Center for Agroforestry, University of Missouri – Columbia.

Plants vary greatly in their physiological and morphological responses to different conditions such as shade, temperature, and moisture (Lin et al., 1999). In agroforestry systems, tree-crop combinations result in the competition for light, water, and nutrients that introduces challenges and complexities not present in conventional agricultural systems (Lin et al., 2009). Minimizing this competition is vital. Proper selection of cover crops for weed management via the quantification of their physiological and morphological behaviors can be challenging, but it is vital in ensuring the success of agroforestry systems (Lin et al., 1998). For example, cool-season cover crops (C_3 plants) grow well in shaded conditions, compared to warm-season cover crops (C_4 pants), which grow well in high light conditions (Lin et al., 1998). If proper cover crop selection is achieved, the potential for weed control can be maximized.

Living mulch

Living mulches are an effective strategy to provide weed control to cropping systems via cover crops (Pfeiffer et al., 2015). Living mulches are cover crops planted either before or with a main crop and are maintained as a living ground cover throughout the growing season (Hartwig and Ammon, 2002). Living mulches aid in weed suppression due to shading and competition for light and water (Akoboundu, 1993). Dense, long-term cover crop plantings are often best for weed control due to the high competition for resources (Fageria et al., 2005). Resource competition is essential for cover crop weed management, but competition with cash crops or trees should be considered. Competition can be minimized in tree-crop interactions by implementing strategic action plans. Vigorous cover crops are often the best for use as a living mulch as they establish quickly, thereby preventing weeds from properly germinating and maturing (Fageria et al., 2005). Not only do the cover crops help to manage weed competition but added nitrogen from leguminous cover crops and nutrient scavenging abilities of grass cover crops help to reduce costly synthetic inputs for future crop production (Curran et al., 2006).

Terminated cover crop residue

Interactions between cover crops and weeds vary depending on whether the cover crop is living or terminated (**Figure 4**) (Teasdale et al., 2007). Research has demonstrated that cover crops that produce a high amount of biomass can be terminated and used to prevent and control the emergence of weeds (Silva, 2014). Use of terminated cover crop residue for weed management was practiced for decades but has been improved to allow planting of cash crops in plant residue (Akoboundu, 1992). A mulch barrier created from the terminated cover crops inhibits weed growth by preventing sunlight from reaching the soil surface (Teasdale et al., 2007). As explained by Silva (2014), termination of cover crops can be achieved using herbicides, or a mechanical roller-crimper mechanism. Silva (2014) explains that herbicide termination is common, but the mechanical roller-crimper allows for a one-time expense, compared to annual expenses for herbicides. Mowing is another option for cover crop termination, but to be effective, must be performed at the correct growth stage to ensure crop termination (Curran et al., 2006). However, mowing of cover crops may lead to uneven distribution of the residue, which can create pockets that allow weeds to emerge (Silva, 2014).

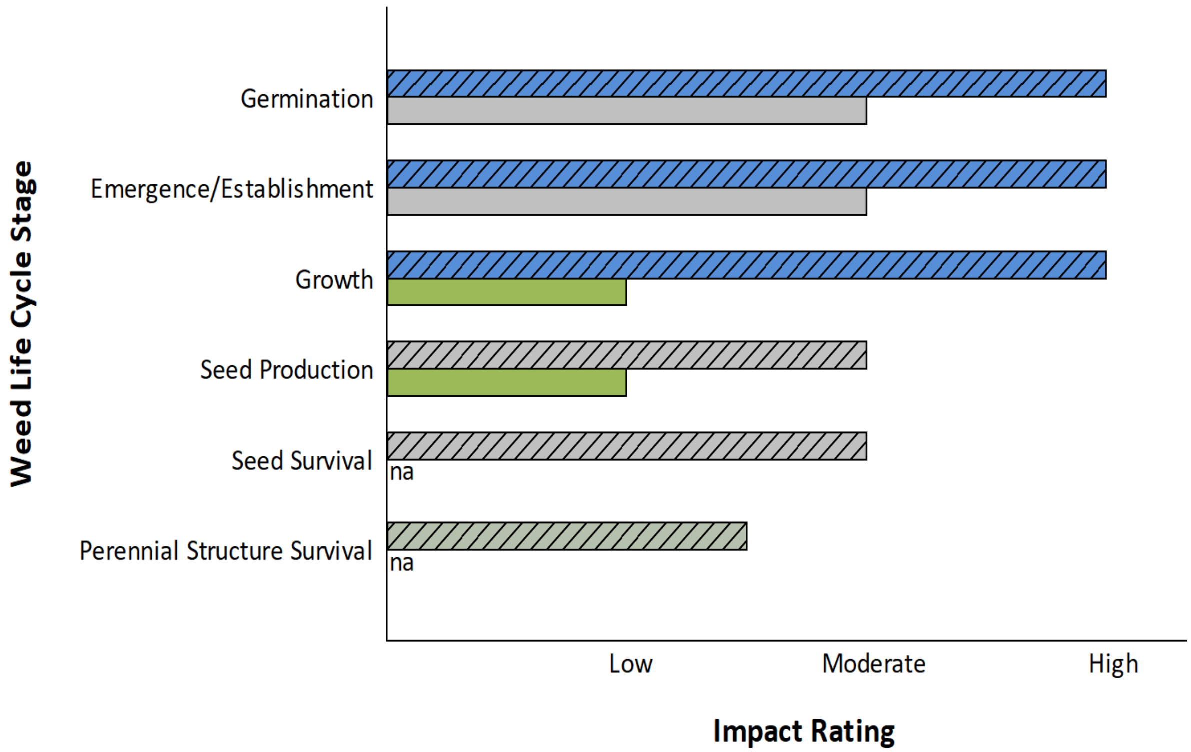

Figure 4. Potential impact of typical live cover crop (top bars with diagonal lines) or cover crop residue (bottom bars with no diagonal lines) within life cycle stages (adapted from Teasdale et al., 2007).

Allelopathy

Allelopathy offers potential for weed control through the production and release of allelochemicals from leaves, flowers, seeds, stems, and roots of living and decomposing cover crop plant material (Weston, 1996). Cover crops can produce a number of bioactive allelochemical compounds that suppress weeds by interfering with weed germination (Weston and Inderjit, 2007). In order for allelopathy to be effective, appropriate conditions must be met before allelopathic chemicals are used for weed seedling control (Weston, 1996). Cover crops selectively provide weed control through their physical presence on the soil surface and by the release of allelochemicals or microbially altered allelochemicals (Weston, 1996). Cover crop residues remaining on the soil surface can physically modify weed seed germination by altering the seed environment (reducing the availability of light, water, and nutrients) and through other types of interference, primarily allelopathy (Creamer et al., 1996). Allelopathic interference with weeds is a systematic approach to weed management in improved cropping systems and can address both the economic and environmental consequences of weeds (Weston and Inderjit, 2007). Practical weed control can be achieved by using allelopathy, without anticipated harm to the environment or increases in weed management costs (Jabran et al., 2015).

Benefits of cover crops

The main objective of this review was to determine the potential of cover crops for weed management. Although cover crops have potential for weed control, they also offer a variety of benefits for improved cropping systems like agroforestry systems. Other benefits of cover crops include, but are not limited to: erosion control, improved soil organic matter, nutrient scavenging/recycling, feed source, and reduced tillage/herbicide use (Curran et al., 2006; Brust et al., 2014). Each of these benefits is discussed further in the following paragraphs.

Erosion occurs most rapidly on agricultural lands where there is no cover (Curran et al., 2006). Soil erosion is a major problem because it reduces the depth of fertile topsoil, creates unwanted gullies in the land, and causes sedimentation of streams (Lovell and Sullivan, 2006). Loss of topsoil by water and wind erosion caused by poor soil management is one of the most substantial factors contributing to deterioration of soil physical, chemical, and biological properties (Fageria et al., 2005). This, in turn, leads to reduced crop production (Fageria et al., 2005). Cover crops provide needed protection for soils when cash crops or primary crops are not present (Curran et al., 2006). Surface runoff is slowed with the presence of cover crops, allowing for improved filtration of water. With improved infiltration, cover crops prevent runoff of nutrients and pesticides from entering surface waters. Therefore, cover crops can contribute significantly to conserving soil and environmental quality (De Baets et al., 2011).

Next, the importance of soil organic matter in improving soil fertility and productivity is well known (Fageria et al., 2005). Like crop residues and manure, cover crops add organic matter to the soil (Curran et al., 2006). The increase in organic matter provided by cover crops occurs slowly over time, but the buildup of organic matter helps to stabilize soil aggregates, makes soil easier to cultivate, increases aeration, and increases soil water holding capabilities (Carter and Stewart, 1996). Cover crops improve soil organic matter compounds that bind primary soil particles in the aggregate, physically and chemically, thus increasing the stability of aggregates and limiting their breakdown during the wetting process (Fageria et al., 2005). The incorporation of cover crops influences transient soil microbial dynamics and nutrient availability at an early growth stage of subsequent crops (De Baets et al., 2011). Conversely, without cover crops, repeated cultivation and lack of soil cover increase the breakdown of soil organic matter and expose soil organic carbon to oxidation, which is lost as atmospheric CO_2 (Fageria et al., 2005).

Besides soil benefits, cover crops can provide essential nutrients to other crops, which is done by legumes fixing atmospheric nitrogen and releasing it back to the soil when they break down (Curran et al., 2006). Certain cover crops, such as grasses, are very efficient at recycling or scavenging for excess nutrients left behind at the end of the growing season (Curran et al., 2006). This is especially apparent with warm-season grass (C_4 plants) cover crops given that their root systems reach deeper soil layers than could provide nutrients that were leached from previous growing seasons (Fageria et al., 2005).

Finally, certain cover crops, especially grass cover crops, can be used for forage or livestock feed by grazing a variety of animals on the land (Curran et al., 2006). An example of grazing in improved cropping systems is silvopasture. Silvopasture is an agroforestry land-use system that is comprised of pasture forage crops between rows of trees (Lin et al., 1998). This intensive land-use system provides the opportunity for cover crops to be used as a potential feed source for livestock. Walter (2018) mentions that managed intensive grazing (MIG) is necessary for silvopasture to ensure that pasture areas are not being overgrazed, as well as for proper tree protection.

Cover crop limitations

As noted above, cover crops offer a multitude of benefits that range from weed control, erosion control, improved organic matter, nutrient scavenging/recycling, and feed source for livestock. Nonetheless, there are some limitations when implementing cover crops for weed control measures.

Cover cropping adds a higher level of complexity and potential ecological interactions that are difficult to predict and manage (Teasdale et al., 2007). Unlike conventional agriculture systems that have a single species, cover cropping can include a multitude of species with various growth patterns and nutrient needs. In certain situations, unmanaged cover crops can act as weeds by competing with primary crops for light, water, and nutrients. Cover crops are also affected by the same chemical and physical factors that they contribute to weed control (Weston and Inderjit, 2007). The bioactive compounds that are produced by cover crops for allelopathic weed suppression can persist in soil systems over time, and although they assist in controlling weeds, these chemicals have the potential to hinder future crop growth (Weston and Inderjit, 2007).

Without proper research into the relationships among specific cover crop and other improved cropping system species, cover cropping has the potential to hinder the growth of other crops rather than suppress weed species.

Cover crops can also add additional costs to a farmstead beyond normal cropping practices and must be managed like any other crops produced in the farm operation (Curran et al., 2006). Additional costs include the cover crop seed, as well as labor, specialized equipment, and maintenance (Curran et al., 2006).

Further, while cover crops provide feed for livestock, that same feed attracts potential pests (Curran et al., 2006). Cover crops provide excellent habitat for wildlife, including rabbits (*Sylvilagus* spp.), mice (*Peromyscus* spp.), and voles (*Arborimus* spp.) that can damage cash crops, as well as young trees (Van Sambeek and Garrett, 2004). Delaying planting of cover crops until after early establishment of other crops can help to minimize mortality of cash crops and young trees from pests.

Overall, cover crops provide some limitations or disadvantages to a farmstead, but these negative effects can be balanced against the positive benefits discussed in the previous sections (Fageria et al., 2005). The use of cover crops for weed management can be challenging, but proper cover crop selection and management can help to ensure that competition in tree/crop combinations is minimized.

5. Cover Crop Species

Legume cover crops

Cover crops can be leguminous or non-leguminous. Leguminous cover crops are used as a source of nitrogen, while acting as a management tool for weed control (Fageria et al., 2005). **Table 1** provides examples of leguminous cover crops that fix atmospheric nitrogen and reduce the need for artificial inputs (i.e., fertilizers) (Fageria et al., 2005). Under favorable climatic conditions, leguminous cover crops that produce high biomass and fix nitrogen tend to have greater effects on increasing crop yields, suppressing weeds, and improving soil properties (Blanco-Conqui, et al., 2012).

There are numerous mechanisms in which legume cover crops control weeds (Fisk et al., 2001). Living leguminous cover crops alter soil moisture conditions and reduce the amount of light reaching weeds in the fall, thereby hindering fall weed germination and affecting weed ability to survive winter (Fisk et al., 2001). Another mode of legume cover crop weed management is the use of terminated high biomass legume residues as mulches or barriers (Silva, 2014). Due to their high biomass inputs, legume cover crops can provide an effective protective soil cover and supply substantial amounts of nitrogen to subsequent crops (Blanco-Conqui et al., 2012). The termination of cover crops is usually done with herbicides, but the roller-crimper noted above offers termination without the use of synthetic herbicides (Silva, 2014). Typical roller-crimpers consist of hollow drums filled with water to add weight, along with blunt blades on the drum that flatten and break cover crop stems (Silva, 2014). A blanket, or barrier, is created by the legume cover crop residue, which alters soil temperatures and reduces light for weed germination.

Grass cover crops

Compared to leguminous cover crops, grass cover crops typically do not provide nitrogen fixing capabilities, but they are excellent scavengers for inorganic nitrogen, phosphorus, and calcium found in agricultural soils (Curran et al., 2006). Examples of grass cover crops are listed in **Table 2**. Grass cover crops typically provide a high amount of biomass that aids in the management of weed species (Snapp et al., 2005). Similar to legume cover crops, grass cover crops provide a number of ways to manage weeds. Fisk et al. (2001) mentions that both legume and grass cover crops alter soil moisture conditions and reduce the amount of available light that is vital for weed germination and seed production. Once again, the roller-crimper mechanism is used for termination of grass cover crops (Silva, 2014), and due to the high biomass grass cover crops provide, they are usually effective at providing a barrier that inhibits weed growth. Grass cover crops can also provide a mechanism unique to that of legume cover crops: allelopathic growth inhibitors. As highlighted previously, allelopathy is an effective weed management tool under appropriate conditions (Weston, 1996). The allelopathic growth inhibitors that grass cover crops release are effective at minimizing weed competition, along with natural competition for light, water, and nutrients.

Additional non-leguminous cover crops are noted in **Table 3**.

6. Conclusions

In recent years, the importance of cover crops for weed management has increased due to concerns for improved crop yields, enhanced soil quality, and reduced chemical inputs (Fageria et al., 2005). Cover crops not only provide weed control, but also additional benefits related to groundwater quality, improved soil organic matter, erosion control, nitrogen fixation, nutrient scavenging/recycling, and a feed source for livestock. Cover crops can be managed to optimize environmental benefits and minimize potential competition from crop and tree production (Teasdale et al., 2007).

In terms of improved cropping systems, such as agroforestry, the use of cover crops can provide reliable weed suppression. The combination of crops, trees, or livestock in agroforestry systems creates complexities not seen in conventional cropping systems. Agroforestry systems require a great amount of knowledge and intensive management in order to be productive. The benefits of agroforestry systems and cover crops coincide; both provide added environmental, ecological, and socio-economic benefits. One farmstead goal is to replace unmanageable weed populations with more manageable cover crop populations (Teasdale et al., 2007).

The use of cover cropping as the sole management method for weed control is not feasible, especially on large-scale operations. Total vegetation control for these agroforestry systems is not always the best choice during tree seedling establishment, wherein soil erosion can occur due to a lack of cover (Alley et al., 1998). A combination of cover crops and traditional methods can be used to manage weed populations, with the goal of phasing out traditional control methods over time.

Overall, the potential for weed management by cover crops in agroforestry systems depends on proper cover crop selection and management. Weeds are controlled by living cover crops outcompeting weeds, terminated residues of cover crops acting as mulch barriers, and allelopathic interactions with weed populations. The use of cover crops as a weed management tool is promising, especially for improved cropping systems like agroforestry. The goal of these cropping systems is to achieve more biodiversity and diversification of revenue streams, while realizing the ecological, environmental, and socioeconomic benefits.

Table 1. Popular **legume** cover crops used for weed management (adapted from Curran et al., 2006).

Species	Annual/Perennial	N-Fixation (nutrient scavenger)	Seeding date	Advantages	Disadvantages
Hairy Vetch (*Vicia villosa* Roth)	Winter annual	N-fixer	August/ early September	-Cold tolerant -High yields -Drought tolerant -Adopted to wide range of soils	-Slow establishment -Matures late in spring -High nutrient requirements
Crimson Clover (*Trifolium incarnatum* L.)	Winter/summer annual	N-fixer	August	-Rapid growth -Shade tolerant -Can be used for forage	-Poor drought and heat tolerance -Plant residue causes problems in no-till systems
Red Clover (*Trifolum pratense* L.)	Perennial	N-fixer	August	-Deep taproot -Tolerates wet soil and shade -Adapted to humid areas	-Slow initial growth -High nutrient requirements
White Clover (*Trifolium repens* L.)	Perennial	N-fixer	August/ spring	-Adapted to most temperate zones -Tolerates high traffic -Heat, drought, and flood tolerant -Can be used as living mulch	-Small yields during hot weather -Can compete with crops if used as living mulch
Birdsfoot trefoil (*Lotus corniculatus* L.)	Perennial	N-fixer	Spring/ early summer	-Fast establishment -Can be used as living mulch	-Can compete with crop if not terminated

Table 2. Popular **grass** cover crops used for weed management (adapted from Curran et al., 2006).

Species	Annual/Perennial	N-Fixation (nutrient scavenger)	Seeding date	Advantages	Disadvantages
Cereal Rye (*Secale cereale* L.)	Annual	Nutrient and moisture scavenger	Fall	-Cold tolerant -Germinates and grows rapidly for quick fall cover and weed suppression -Various uses: cover crop or food source -Allelopathy suppresses weed growth and germination	-Can be difficult to manage when mature -Potential crop suppression due to allelopathy
Spring Oats (*Avena sativa* L.)	Summer annual	Nutrient scavenger	Spring or fall	-Rapid growth in cool weather, which is ideal for quick cover -Can be used as cover crop or food source	-Winter kills -Susceptible to pests and diseases
Perennial Ryegrass (*Lolium perenne* L.)	Perennial	Nutrient and moisture scavenger	Spring or fall	-Tolerates wide range of soil conditions -Quick establishment for weed suppression and cover -Can be used as living mulch	-Low heat tolerance -Can winter kill
Timothy (*Phelum pratense* L.)	Perennial	Nutrient and moisture scavenger	Spring or late summer/ fall	-Tolerates wet conditions -Good nutrient uptake	-Slower to establish -Does not graze well

Table 3. Other popular cover crops used for weed management (adapted from Curran et al., 2006).

Species	Annual/Perennial	N-Fixation (nutrient scavenger)	Seeding date	Advantages	Disadvantages
Buckwheat (*Fagopyrum esculentum* Moench)	Summer annual	Nutrient scavenger (i.e., P and Ca)	Spring or fall	-Tolerates wide variety of soils -Establishes quickly for weed suppression -Soil conditioner	-Limited growing season
Brassicas (*Cruciferae* family) (e.g., rape, turnip, kale, radish)	Annual	Nutrient scavenger (i.e., N, P, and Ca)	Spring or fall	-Establishes quickly in cool weather -Deep root system -Grows well even in shorter days -Drought tolerant	-Low tolerance to wet soils -Winter kills

7. References

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