Chapter 22

Integrating Herbicides in a High-Residue Cover Crop Setting

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Additional information is available at the end of the chapter

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1. Introduction

Sustainable agriculture requires the use of multiple, integrated weed management practices to ensure long-term viability. A number of cultural, mechanical, and chemical weed control options can be utilized in a production system to reduce weed interference and safeguard crop yield. The dependence on one single weed control strategy may result in short-term success; however, long-term use can lead to multiple setbacks including poor soil health, reduced crop production, and increasing herbicide resistance. In turn, employing multiple weed control tactics simultaneously may prove difficult without previous knowledge as to how best to implement an integrated weed management system. To that end, this chapter is dedicated to illustrating successful herbicide use in conjunction with cover crops and their residues, practices proven not only to suppress weed germination and growth, but also to reduce soil erosion and water runoff and build soil organic matter and thus subseqent productivity.

Use of cover crops, particularly those producing high amounts of biomass (greater than 4,500 kg ha^{-1}), can provide numerous benefits for a cropping system [1]. However, care must be taken when choosing herbicides to apply to these cover crops both prior to and after primary crop planting. This chapter provides an overview of effective herbicide choices for use prior to and within cover crop as well as efficient application methods for use after planting the primary crop(s). We also discuss herbicide interception by cover crop residue and means to control reduced efficacy due to interception. It is hoped that this summary will aid in the adoption of sustainable farming practices to ensure successful agricultural productivity for future generations.

2. Conservation agriculture

As demands are placed on agriculture to produce increasing yields for a growing global population, the need to implement systems with high productivity and sound environmental standards is key to ensuring agricultural sustainability for future generations. To this end, conservation agriculture is a systems-based approach for food, feed, and fiber production that utilizes a number of practices aimed at maintaining yields while limiting energy and chemical inputs, minimizing soil degradation and erosion, and reducing long-term, detrimental impacts to the environment [2]. Conservation agriculture is comprised of many different management practices, particularly cultural techniques such as crop rotation, planting date, and seeding rate, that can reduce dependence on chemical inputs for successful yield production. Moreover, limited tillage practices, or conservation-tillage, is essential to conservation agriculture systems to ensure soil quality, reduce runoff, and lessen energy consumption on agricultural lands.

2.1. Conservation tillage

Conservation-tillage, or reduced-tillage, has been proven to provide multiple benefits in agricultural settings. In addition to erosion and runoff control, soil health improvement, and reduced energy demands, reduced-tillage practices can produce crops yields similar to that of conventional systems [3-5]. The use of reduced-tillage, however, can alter weed communities. Seed production by annual weed species remains, in most part, on the soil surface where it is subject to increased decomposition and predation. With reduced competition and minimized soil disruption, perennial weed species can become established and dominate the weed community in conservation-tillage [6]. To aid in the control of both annual and perennial weeds, the use of cover crops for ground cover can reduce herbicide requirements in conservation-tillage settings.

2.2. Cover crops

A number of cereal and legume cover crops are utilized in various crop productions for several purposes. Currently, a large portion of cover crops are planted as a green manure which are turned under prior to sowing the primary crop [7,8]. In reduced-tillage, however, cover crops are grown as a ground cover and remain on the soil surface after cover crop termination. In addition to further reducing soil erosion, increasing soil organic matter, and improving water infiltration, cover crops can provide a level of weed suppression both prior to and during the primary growing season [9]. When compared to fallow conservation-tillage systems, cover crops offer increased weed control through direct resource competition while actively growing as well as through shading and/or allelopathy after termination. Covers grown to produce high levels of biomass, in particular, can increase shading of germinating weed species and provide greater ground cover for an extended period during the growing season. When employing cover crops, however, knowledge concerning herbicide use both during cover crop production and primary crop growth is essential.

2.3. Herbicide use

2.3.1. Cover crop establishment and termination

To produce substantial cover crop biomass, it is imperative to adequately manage cover crop production. Besides using correct seeding rates, early planting dates, and sufficient fertilizer applications, it is important to be aware of herbicide applications made prior to cover crop establishment. Often times, postemergent (POST) herbicides applied late season or post-harvest can have residual carryover than may be detrimental to cover crops. Rotation restrictions listed on herbicide labels should be referred to when planning POST applications and cover crop species.

To manage cover crops before cash crop planting, herbicides are typically utilized for cover crop termination. Most often, these herbicides, such as glyphosate and glufosinate, are non-selective with little to no carryover risk. However, consideration should be given to in-season chemical weed control regimes in order to limit repeated applications of a single herbicide mode of action. Moreover, care should be taken to avoid reduced herbicide rates applied for cover termination to reduce the risk of herbicide resistance [10]. Recent research has focused on mechanical termination with a roller or crimper which may reduce or eliminate the need of these herbicides for cover crop termination [11].

2.3.2. Cash crop establishment and management

Although use of in-season herbicides can be substantially reduced when using high-residue cover crops, some chemical applications are generally required to achieve the most effective weed suppression and minimize crop loss due to weed competition. While an ideal agricultural system would require no chemical inputs for sufficient weed control, practicality dictates the use of herbicides to guarantee crop yield since no system, as of yet, exists that can successfully suppress weed populations without intensive labor or mechanical requirements. To this end, cover crops are a means to minimize, rather than eliminate, herbicide inputs in crop systems. In recognizing the fact that the majority of agricultural systems will require chemical weed control measures for optimum crop production even when utilizing cover crops, it is essential to understand how cover crops affect herbicide selection and efficacy for each crop.

Primarily, the use of reduced-tillage and cover crops eliminates the ability to utilize preplant incorporated herbicides which offer residual soil activity [11]. Furthermore, cover crop residue can impede preemergent (PRE) herbicide applications from reaching the soil surface, reducing herbicide efficacy [12]. While postemergent chemical weed control can be effective alternatives in these settings, many weed species can prove to be difficult to control if not killed early in the season. Moreover, resistance concerns essentially necessitate the use of preemergent herbicides with differing mechanisms of action to avoid selection pressure for resistant weed biotypes [13].

Along with many cultural pracitces, production of crops under reduced-tillage with cover crops requires development of specific herbicide regimes to ensure minimal chemical inputs while achieving sufficient weed control to allow for successful crop production. The following sections review major crops produced globally, describe research conducted in respect to reduced-tillage production, as well as list available herbicides for use when using reduced-tillage and cover crops. These reviews are designed to provide information that can be beneficial for producers implementing conservation-tillage.

3. Wheat

Global production of wheat (*Triticum aestivum* L.) was estimated at approximately 217 million hectares in 2010 [14] representing the largest single crop, in area grown, and providing approximately 19% of the caloric intake of the world's diet [15]. In recent years, concerns have been noted over stagnant wheat yields due to drought and rising temperatures attributed to global warming [16]. Efforts to maintain current wheat production levels and identify potential measures to aid in increasing yield have led researchers to explore conservation practices in wheat systems. In addition to preserving high crop yields, long-term conservation systems are intended to protect environmental quality and reduce chemical and energy inputs necessary for crop production. Components of conservation systems such as reduced- or no-tillage can produce crop yields equal to or exceeding conventional tillage practices while reducing erosion, water runoff, and increasing water infiltration.

Much research has been conducted to evaluate wheat productivity in conservation-tillage practices. Reports reveal similar or increased grain yield for reduced-tillage compared to conventional tillage systems [17-19]. With little or no tillage operations, some chemical applications are required to achieve successful levels of weed control; however, with herbicide applications, weed species have been effectively controlled below levels that could reduce yield [20]. To offset the herbicide needs in conservation-tillage, evaluations of cover crops as ground cover have been conducted. Crops such as mustard (*Sinapis alba* L.), pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.) have proven to be good choices with little yield differences [21]. However, other reports show negative impacts on wheat production when implementing cover crops prior to wheat production for reasons such as increased weed competition, primarily *Bromus* spp., and reduced fertilizer uptake [22].

Like most crops produced in conservation-tillage, herbicide options may be limited to a degree whether utilizing a cover crop or not. With reduced-tillage, preplant incorporation of residual herbicides cannot be utilized. Moreover, when planting into cover crops, soil-applied pre-emergent herbicides may be less effective due to interception by crop residue. When planting wheat, preplant burndown herbicides may be necessary to control early weeds. POST herbicides are also necessary to control weeds that germinate after planting. Table 1 lists many of the herbicide options for use in conservation-tillage systems for wheat production.

4. Maize

Maize, or corn (*Zea mays* L.), is one of the most economically important grain crops worldwide with 162 million ha produced in 2010 [2]. In addition to being a staple in human and livestock diets in many countries, corn is also used for bioethanol production and the manufacturing of many non-food products. Consumption of corn and products derived from corn continues to increase. Given the demand, it is imperative for sustainable production systems that produce high yields while preserving long-term productivity of the land to be implemented.

Conservation-tillage practices have been researched and utilized for several decades in some regions such as the Midwest in the United States. As with many other crops, some variability has been noted for corn yield in no-tillage systems compared to conventional tillage methods. However, many reports show at least equal corn yields can be achieved when tillage practices are reduced [3]. Adequate yield potential, coupled with the reduction of on-farm expenses, have made conservation-tillage systems a good fit for corn production.

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Carfentrazone	Aim® [23]	Preplant Burndown	Non-selective control of emerged broadleaves and grasses
Glufosinate	Liberty® [24]		
Glyphosate	Roundup WeatherMax®[25]		
Paraquat	Gramoxone® [26]		
Chlorsulfuron + Metsulfuron	Finesse® [27]	PRE or POST[b]	*Bromus* species, annual ryegrass (*Lolium multiflorum*), kochia (*Kochia scoparia*)
Pyrasulfotole + Bromoxynil	Huskie™ [28]	Early POST	Emerged broadleaf seedlings such as dandelion (*Taraxacum officinale*); suppression of established dandelion and henbit (*Lamium amplexicaule*)
Thifensulfuron + Tribenuron	Harmony® Extra [29]	POST	Actively growing broadleaves, wild garlic (*Allium vineale*); suppression of Canada thistle (*Cirsium arvense*)
Clearfield wheat			
Imazamox	Beyond® [30]	POST	Broadleaves henbit and chickweed (*Stellaria media*), grasses barnyardgrass (*Echinochloa crus-galli*), jointed goatgrass (*Aegilops cylindrica*), volunteer cereals (non-Clearfield types)

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence; POST, postemergence.

Table 1. Herbicides for use in reduced-tillage wheat production.

A major limiting factor to adopting reduced-tillage in corn production is the concern of less effective weed control. Tillage has long been used as a means for weed seed burial which reduces the number of seeds in the upper portion of the soil, the area most favorable for germination for most species. In addition to weed seed remaining in the upper layer of soil, shifts in weed species have also been noted. With the implementation of conservation-tillage, most crop systems experience a shift in weed species from annuals to perennials dominating the weed community.

Perennial weed species, largely controlled with tillage practices, can thrive on less disturbed crop land. For effective weed control, producers implementing reduced-tillage have relied on increased herbicide applications. To curb herbicide use, cover crops have been adopted in conjunction with reduced-tillage corn systems. Research has shown that utilizing a legume or grain cover crop can reduce weed density and growth while not affecting corn yield [31,32]. For corn in particular, cover crops offer a potential benefit in addition to weed suppression. Adequate nitrogen availability is essential for corn development. The use of legume cover crops, such as hairy vetch (*Vicia villosa* Roth), red clover (*Trifolium pratense* L.), or medics (*Medicago* spp.), may provide a portion of corn nitrogen requirements and reduce fertilizer inputs into the system [33]. Some research indicates that legume covers do not reduce fertilizer requirements but improves grain production with standard fertilizer applications [34]. Other research shows that legume covers can provide some nitrogen required for successful corn production[35,36]. Selecting the right legume cover crop for maximum nitrogen contribution with timely availability for corn uptake is key for utilizing these crops as nitrogen sources.

Use of burndown herbicides prior to corn planting is critical for early season weed control when using cover crops. A residual herbicide applied in conjunction with the herbicide used for cover crop termination can broaden weed species controlled as well as extend control into the season. A number of PRE herbicides are available that can be applied without incorporation into the soil and are effective even with plant residue on the soil surface. These herbicides and POST herbicide choices that can be successfully utilized in conservation-tillage corn with cover crops are listed in Table 2.

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Glufosinate	Liberty® [24]	Preplant burndown	Emerged weed species
Glyphosate	Roundup WeatherMax® [25]		
Paraquat	Gramoxone® [26]		
2,4-D	Agri Star® 2,4-D [37]		
Atrazine	Aatrex® [38]	Preplant or PRE[b]	Broadleaves such as kochia (*Kochia scoparia*); suppression of foxtail (*Setaria* spp.), velvetleaf (*Abutilon theophrasti*). Can also be applied POST

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Flumioxazin	Valor® [39]		Broadleaf species such as horseweed (*Conyza canadensis*); suppression of grass species such as panicum (*Panicum* spp.) and goosegrass (*Eleusine indica*)
Pendimethalin	Prowl® [40]		Germinating, small-seeded grass and broadleaf species such as crabgrass (*Digitaria* spp.) and common lambsquarters (*Chenopodium alba*)
S-metolachlor	Dual Magnum® [41]		Grass and broadleaf species such as foxtail and *Amaranthus* spp.
Carfentrazone	Aim® [23]	POST[c]	Certain broadleaf weed control; tank mix with atrazine or dicamba
Bromoxynil	Buctril® [42]		Broadleaf weeds such as burcucumber (*Sicyos angulatus*), giant ragweed (*Ambrosia trifida*)
Dicamba	Banvel® [43]		Annual broadleaf species as well as certain perennial species such as dock (*Rumex* spp.) and wild onion (*Allium* sp.)
Mesotrione	Callisto® [44]	POST	Broadleaf species such as wild mustard (*Sinapis arvensis*), nightshade (*Solanum* spp.), and Canada thistle (*Cirsium arvense*)
Tembotrione	Laudis® [45]		Broadleaf and grass species such as common chickweed, purple deadnettle (*Lamium purpureum*), *Amaranthus* spp., and large crabgrass (*Digitaria sanguinalis*)
Ametryn	Evik® [46]	POST-directed spray	Grass species such as Texas panicum, goosegrass, and foxtail
Linuron	Lorox® [47]		Broadleaf and grass species such as dog fennel, common ragweed (*Ambrosia artemisiifolia*), velvetleaf, and annual ryegrass (*Lolium multiflorum*)
Clearfield Corn			
Imazethapyr + Imazapyr	Lightning® [48]	POST	Broadleaves, grasses, and sedges such as kochia, ragweed, quackgrass (*Elytrigia repens*), and nutsedge (*Cyperus* spp.)
LibertyLink Corn			
Glufosinate	Liberty®	POST	Broadleaf and grass species; ragweed, horseweed, johnsongrass seedlings
Roundup Ready Corn			

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Glyphosate	Roundup Weathermax®	POST	Nonselective control of some broadleaf and grass species
Glyphosate + *s*-metolachlor + atrazine	Expert® [49]	PRE or POST	Annual broadleaves and grasses; perennials such as quackgrass, dandelion (*Taraxacum officinale*), and Canada thistle

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence.

[c]POST, postemergence.

Table 2. Herbicides for use in reduced-tillage maize production.

5. Rice

Production of rice (*Oryza sativa* L.) in 2010 was near 154 million ha worldwide [2]. In many regions, rice provides nearly half or more of calories consumed by humans [50] and is the most important grain crop grown. Rice yield has steadily grown in the past several decades due to breeding and fertilizer advancements; however, it is necessary for rice yield to continue to improve in order to meet increased demands by a growing world population. Given that little land exists in rice-producing countries to expand production, it is necessary for methods to be established that can continue yield improvement without depleting future soil productivity.

Wetland, transplant rice production is the dominant and highest yielding rice system in most regions [50, 51]. However, the water and energy requirements may limit rice production as competition for resources increases [52]. To reduce strain on environmental and economic resources and to ensure sustainable rice systems in the future, dry-seeded rice production has been implemented in some areas [53]. Dry-seeded rice production can be initiated in conjunction with conservation-tillage with fewer water demands, lower energy and labor requirements, and reduced soil erosion. Research has reported that dry-seeded rice in no-tillage can be a successful alternative to conventional systems [52].

A limiting factor to widespread adoption of dry-seeded, reduced-tillage rice, however, is reduced weed control. For rice, transitioning from wetland, conventional systems to a dry system with reduced-tillage can affect weed compositions in multiple ways. Standing water can reduce germinating weed seeds while the transplanted rice becomes established; removing this water barrier can increase weed numbers [54]. Additionally, reduced-tillage practices can result in an increase of weed seed germination due to less seed burial.

In dry-seeded rice, mulches have been suggested as a means to combat weed increases [51]. Little research has been conducted to fully understand the benefits of cover crops for weed control in rice; however, legume covers have been associated with increased rice yield and reduced weed biomass in upland rice [55]. Future research needs include addressing the effects of cover crops on rice production in dry-seeded rice systems.

Due to challenging weed issues in rice systems, particularly dry-seeded rice, herbicide use will continue to be necessary for effective weed suppression in both conventional and reduced-tillage systems. The implementation of cover crops into these systems may lessen the herbicide requirements but will not eliminate the use of chemicals altogether. Currently there are a number of preemergent and postemergent herbicides available for use in rice production (Table 3); however, as dry-seeded, conservation-tillage rice systems increase in popularity, more herbicide options may become available.

Herbicide			
Common Name	**Trade Name**[a]	**Application Timing**	**Weed Species Controlled**
Clomazone	Command®[56]	PRE[b]	Grass species such as barnyardgrass (*Echinochloa crus-galli*), crabgrass (*Digitaria* spp.), and panicum (*Panicum* spp.)
Halosulfuron	Permit® [57]		Broadleaf species such as dayflower (*Commelina erecta*) and kochia (*Kochia scoparia*). Broadleaf and grass species may be controlled with a POST application.
Pendimethalin	Prowl® [40]		Germinating, small-seeded grass and broadleaf species such as crabgrass (*Digitaria* spp.), foxtail, and common lambsquarters (*Chenopodium alba*)
Quinclorac	Facet® [58]		Broadleaf and grass species such as morningglory (*Ipomoea* spp.), and barnyardgrass. Can also be applied POST
Thiobencarb	Bolero® [59]		Grass and broadleaf species such as barnyardgrass, dayflower (*Commelina communis*), and eclipta (*Eclipta alba*)
Acifluorfen	Ultra Blazer® [60]	POST[c]	Grasses and broadleaves such as foxtail (*Setaria* spp.), panicum, and eclipta
Bensulfuron	Londax® [61]		Broadleaf and sedge species, particularly aquatic weeds such as ducksalad (*Heteranthera limosa*) and ricefield bulrush (*Scirpus mucronatus*)
Bentazon	Basagran® [62]	POST	Broadleaf and sedge species such as dayflower, eclipta, and yellow nutsedge (*Cyperus esculentus*)
Carfentrazone	Aim® [23]		Broadleaf species such as common cocklebur (*Xanthium strumarium*), dayflower, and *Amaranthus* spp.

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Propanil	Stam® [63]		Grass, rush, and broadleaf species such as barnyardgrass, spikerush (*Eleocharis* spp.), and curly dock (*Rumex crispus*)
Cyhalofop	Clincher® [64]	After Flooding	Grass species such as barnyardgrass, broadleaf signalgrass (*Brachiaria platyphylla*), and junglerice (*Echnochloa colona*)
2,4-D	Agri Star® 2,4-D [37]		Annual and perennial weed species such as cocklebur, morningglory, and dock
Clearfield Rice			
Imazamox	Beyond® [30]	POST	Grass and broadleaf species such as morningglory, barnyardgrass, and panicum
Imazethapyr	Newpath® [65]		Grass, sedge, and broadleaf species such as barnyardgrass, morningglory, and nutsedge
Imazethapyr + Quinclorac	Clearpath® [66]		Grass, sedge, and broadleaf species such as junglerice, eclipta, morningglory, and nutsedge

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence.

[c]POST, postemergence.

Table 3. Herbicides for use in reduced-tillage rice production.

6. Soybean

Production of soybean [*Glycine max* (L.) Merr.], estimated at 102 million ha in 2010 [2], meets a number of livestock and human food needs as well as industrial demands for use in products such as paints, lubricants, and biofuel. Due to its diversity of uses, the soybean is an important field crop for much of the world. In light of the value of soybeans, it is essential to establish sustainable growing practices to ensure global demand continues to be met.

Implementation of conservation practices, such as reduced-tillage, can be utilized as components of alternative management systems replacing conventional systems to provide erosion and runoff control while reducing labor and cost inputs. In the United States, in fact, approximately 80% of soybeans were produced with some form of conservation-tillage by 2006 [67]. This increase in conservation-tillage can be attributed to the environmental and economic benefits achieved with reduced-tillage as well as the commercial availability of herbicide-tolerant soybeans, which have made successful chemical weed control achievable with the use of fewer herbicides.

Early work in conservation-tillage soybean have reported equal or improved yield in soybean with reduced-tillage compared to conventional systems [68, 69]. Previous research has also examined soybean systems planted behind wheat or a cover crop such as rye with improved weed control being noted when compared to a fallow system [70] and greater yield with a cover crop than with just the previous crop's stubble [71]. The inclusion of plant residue, either from a cover crop or a previous crop, provides a level of weed control by acting as a physical barrier for germinating weed seed or through allelopathic inhibition released by some cover crop species. The weed control provided by ground cover is crucial in a no-till practice due to the loss of control from tillage reduction and the shift towards more difficult to control perennial weed species.

While cover crops and plant residue have been identified as means to reduce weed emergence when implemented in reduced-tillage practices further measures are required to keep the weed population below an acceptable level [70]. Many cultural practices, such as crop rotation, row spacing, and planting date, can be manipulated in such a way as to reduce weed populations; however, herbicide use is still necessary in many systems.

As with most field crops grown in conservation-tillage systems, soybean production with reduced-tillage has heavily relied on postemergent herbicide applications. Use of cover crops in these systems may also contribute to the tendency for fewer PRE herbicides due to interception concerns. However, the increase in herbicide-resistant weed species such as Palmer amaranth (*Amaranthus palmeri* S. Wats) and horsweed [*Conyza canadensis* (L.) Cronq.] in herbicide resistant crops, like soybean, necessitates the use of multiple herbicides to slow the development of weed resitance and safeguard the effectiveness of current herbicide options for the future. Table 4 provides a partial list of herbicides that can be utilized in reduced-tillage soybean with cover crops.

Herbicide			
Common Name	**Trade Name**[a]	**Application Timing**	**Weed Species Controlled**
Glufosinate	Liberty® [24]	Preplant Burndown	Emerged weed species
Glyphosate	Roundup WeatherMax® [25]		
Paraquat	Gramoxone® [26]		
2,4-D	Agri Star® 2,4-D [37]		
Clomazone	Command® [56]	PRE[b]	Grasses and broadleaves such as crabgrass (*Digitaria* spp.), panicum (*Panicum* spp.), velvetleaf (*Abutilon theophrasti*), and Florida beggarweed (*Desmodium tortuosum*)
Dimethenamid	Outlook® [72]		Grass and broadleaf species such as foxtail (*Setaria* spp.), panicum, and *Amaranthus* spp.
Flumioxazin	Valor® [39]		Broadleaf species such as horseweed (*Conyza canadensis*); suppression of grass species such as panicum and goosegrass (*Eleusine indica*)

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Imazaquin	Scepter® [73]		Broadleaf and grass species such as morningglory (*Ipomoea* spp.), velvetleaf, and foxtail
Metribuzin	Metribuzin [74]		Broadleaf and grass species such as *Amaranthus* spp.and broadleaf signalgrass (*Brachiaria platyphylla*)
Pendimethalin	Prowl® [40]		Grass and broadleaf species such as panicum and *Amaranthus* spp.
S-metolachlor	Dual Magnum® [41]		Grass and broadleaves such as barnyardgrass (*Echinochloa crus-galli*), crabgrass, and Florida pusley (*Richardia scabra*)
Bentazon	Basagran® [62]	POST[c]	Broadleaf weeds such as coffee senna (*Senna occidentalis*) and velvetleaf
Chlorimuron	Classic® [75]		Broadleaf weeds such as Florida beggarweed and morningglory
Cloransulam	FirstRate® [76]		Broadleaf weeds such as common cocklebur (*Xanthium strumarium*) and velvetleaf
Fluazifop	Fusilade® [77]		Annual and perennial grass species such as crabgrass and bermudagrass (*Cynadon dactylon*)
Imazethapyr	Pursuit® [78]		Broadleaf and grass species such as morningglory and crabgrass
Lactofen	Cobra® [79]		Broadleaf species such as croton (*Croton* spp.) and Florida beggarweed
Sethoxydim	Poast® [80]		Grass species such as foxtail, crabgrass, and panicum
LibertyLink Soybean			
Glufosinate	Liberty®	POST	Broadleaf and grass species such as *Amaranthus* spp., morningglory, and goosegrass
Roundup Ready Soybean			
Fomesafen + Glyphosate	Flexstar® [81]	POST	Broadleaf and grass species such as morningglory, velvetleaf, and broadleaf signalgrass
Glyphosate	Roundup WeatherMax®	POST	Grass and broadleaf species such as Florida beggarweed, crabgrass and groundcherry

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence.

[c]POST, postemergence.

Table 4. Herbicides for use in reduced-tillage soybean production.

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7. Cotton

Cotton production around the world is estimated at approximately 23 million tonnes (lint production) [2] with China, India, and the United States being the top producers [82]. Efforts to adopt sustainable cotton practices have led producers to utilize conservation-tillage systems in cotton production. Besides environmental benefits achieved with reduced-tillage, major economic advantages can be realized due to reduced time, labor, and fuel requirements when operating with less tillage. Prior to the introduction of herbicide-resistant crops, adoption of reduced-tillage was difficult due to control of weed species required multiple and costly herbicide inputs [13]. In some instances, effective herbicides were not available to control problematic weed species such as perennials that can thrive in reduced-tillage. When glyphosate-resistant cotton was made available, reduced-tillage became practical since a broad spectrum of weed species could be controlled with a single herbicide [83].

Extensive research has been carried out in conservation-tillage cotton with positive benefits seen for cotton yield [84-86]. Moreover, with herbicide-resistant cotton varieties, weed control has been as successful as conventional tillage cotton. Because of this success, conservation-tillage practices have been widely adopted in areas such as the southeastern United States. This dependence on a single herbicide, however, has led to the appearance of herbicide-resistant weed species and now threatens the feasibility of reduced-tillage cotton production. Currently, research efforts are focused on identifying ways to ensure the long-term viability of conservation-tillage while controlling established populations of herbicide-resistant weed species and reducing the risk of future development of resistant weeds.

Multiple weed management tactics are necessary to control weed resistance development with cover crops playing an important role in resistance management. The use of cover crops, particularly high-residue crops such as rye and black oat, can reduce herbicide inputs through shading and allelopathy. The use of high-residue crops allows for maximum shading of the soil surface during the beginning of the season while also providing a ground cover for a longer period into the growing season. Cover crops, along with multiple herbicide modes of action and rotation, have been shown to effectively control weeds in reduced-tillage cotton [87, 88].

A number of herbicide choices are available for use with conservation-tillage cotton (Table 5). PRE herbicides are especially important in early-season weed control to ensure management of weed species that are difficult to control later in the season. Although concerns have been raised as to whether cover crops reduce the efficacy of PRE herbicides, it has been suggested that any loss in weed control due to herbicide interception is offset by the control provided by cover crop residue [89-91].

Herbicide			
Common Name	Trade Name[a]	Application Timing	Weed Species Controlled
Dicamba	Banvel® [43]	Preplant Burndown	Emerged weed species
Flumioxazin	Valor® [39]		
Glufosinate	Liberty® [24]		

Herbicide			
Common Name	**Trade Name[a]**	**Application Timing**	**Weed Species Controlled**
Glyphosate	Roundup WeatherMax®[25]		
Paraquat	Gramoxone® [26]		
Clomazone	Command® [56]	Preplant or PRE[b]	Grasses and broadleaves such as crabgrass (*Digitaria* spp.), panicum (*Panicum*spp.), velvetleaf (*Abutilon theophrasti*), and Florida beggarweed (*Desmodium tortuosum*)
Fluometuron	Cotoran® [92]		Grasses and broadleaves such as signalgrass (*Brachiaria sp.),* horseweed (*Conyza canadensis*) and sicklepod (*Senna obtusifolia*)
Pendimethalin	Prowl® [40]		Grass and broadleaf species such as foxtail (*Setaria* spp.), panicum, and *Amaranthus* spp.
Prometryn	Caparol® [93]		Annual grass and broadleaves such as groundcherry (*Physalis* sp.), Florida pusley (*Richardia scabra*), and panicum
S-metolachlor	Dual Magnum®[41]		Grass and broadleaves such as barnyardgrass (*Echinochloa crus-galli*), crabgrass, and Florida pusley
Clethodim	Select® [94]	POST[c]	Grass species such as crabgrass, panicum, and foxtail
Herbicide			
Common Name	Trade Name	Application Timing	Weed Species Controlled
Quizalofop	Assure® [95]		Annual and perennial grasses such as foxtail, goosegrass (*Eleusine indica*), and bermudagrass (*Cynodon dactylon*)
Sethoxydim	Poast® [80]	POST	Grass species such as foxtail, crabgrass, and panicum
Trifloxysulfuron	Envoke® [96]		Broadleaf and grass species such as coffee senna (*Senna occidentalis*), barnyardgrass, and Florida beggarweed
Diuron	Direx® [97]	POST-directed spray	Broadleaf and grass species such as sicklepod, velvetleaf, and crabgrass
Linuron	Linex® [98]		Broadleaves and grasses such as morningglory, Florida pusley, and panicum
MSMA	MSMA [99]		Grass and broadleaf species such as crabgrass, Florida beggarweed, and *Amaranthus* spp.

Herbicide			
Common Name	**Trade Name**[a]	**Application Timing**	**Weed Species Controlled**
LibertyLink Cotton			
Glufosinate	Liberty®	POST	Broadleaf and grass species such as *Amaranthus* spp., morningglory, and goosegrass
Roundup Ready Cotton			
Glyphosate	Roundup WeatherMax®	POST	Grass and broadleaf species such as Florida beggarweed, crabgrass, foxtail, groundcherry, and velvetleaf

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence.

[c]POST, postemergence.

Table 5. Herbicides for use in reduced-tillage cotton.

8. Peanut

Groundnut, or peanut (*Arachis hypogaea* L.), was planted on approximately 21 million ha between 2011 and 2012 wordwide with top production occurring in China, India, Indonesia, the United States, and some African countries such as Nigeria, Senegal, and Sudan [100]. Besides being a nutrient rich food source, the peanut is utilized for its oil in cooking and manufacturing as well as a livestock feed. In the United States, peanuts offer an exceptional rotational crop with cotton to replenish soil nitrogen. The benefits of peanuts to a cotton system, which have been shifting toward long-term, reduced-tillage practices, have necessitated the adoption of minimum tillage practices in peanut production as well.

The increased farming costs of conventional tillage systems have spurred producers to implement conservation-tillage to reduce expenses; however, peanut growers face unique difficulties when using these systems [101,102]. Particularly, concerns over peanut response to reduced-tillage due to peanut growth habits have required research in order to identify successful means of conservation-tillage integration into peanut production [102, 103].

Peanut yield variability under reduced-tillage compared to conventional tillage has been noted as one of the greatest concerns when adopting conservation-tillage practices [101,102]. Inconsistent yield response by peanut has been noted in previous studies investigating conservation-tillage. Research has reported yields of peanut to be reduced or equal to conventionally tilled peanut [101, 104]; other studies have shown reduced-tillage peanuts to produce equally or greater than conventional tillage peanuts [103,105]. Research efforts continue to recognize the contributing factors that affect peanut response to tillage systems.

Weed management in conservation-tillage peanut is also a concern for producers. Weed control in peanut, regardless of tillage system, can be problematic due to the extended growing season and unique growth habits [106,107]. Generally, peanut production requires an incorporated residual as well as a POST herbicide to provide effective weed control under the slow-closing canopy of peanut [107]. Moreover, in-season cultivation for weed management cannot be implemented due to the potential to damage developing peanut pods [106,108].

Weed control in reduced-tillage peanuts can be even more difficult than in conventional tillage due to the loss of weed control through seed burial and the inability to utilize preplant incorporated herbicides [109]. This results in increased dependence on post emergent herbicides which may or may not control the number of perennial weed species that may predominate in a reduced-tillage setting; the loss of effective weed management can reduce peanut productivity due to weed competition [102,107].

Utilization of cover crops in peanut systems may offer beneficial weed control while reducing the need for increased postemergent herbicide applications. Research has shown effective weed control with cover crops in strip-tillage peanut systems that use a dinitroaniline preemergent herbicide over cover crop residue [107]. Other effective herbicides used in conservation-tillage peanut systems are listed in Table 6.

9. Herbicide interception

Preemergent, residual herbicides must reach the soil surface to be effective. When spraying over cover crop residue, herbicide applications can be intercepted and absorbed prior to reaching the soil surface. Herbicides, such as acetochlor, chlorimuron, and oryzalin have been shown to be impeded by plant stubble [113,114]. While timely rainfall can move herbicides to the soil, some portion of herbicide can be retained in the residue.

Herbicide amounts intercepted by stubble can affect weed control achieved with the herbicide; efficacy can be reduced by cover crops either through physical interception preventing soil contact or through increased microbial activity in the residue speeding herbicide degradation [115]. Increases in soil organic matter from extended conservation-tillage practices may also increase herbicide adsorption within the soil [116]. Additionally, herbicide persistence and carryover risks may be increased when applied to residue [114]. Certain crops may be susceptible to herbicides at low doses that can persist in cover crop residue that would otherwise have dissipated in bare soil. However, little research has been done to determine the extent of persistence for most herbicides.

Methods to reduce herbicide interception are limited when using cover crops. Interception could potentially be managed, particularly in strip-till operations, through banded herbicide applications over the row allowing for in-row weed control while reducing herbicide inputs. Furthermore, a water-based, microencapsulated herbicide formulation, like Prowl $H_2O^®$ (pendimethalin), may allow more herbicide to reach the soil after a rain event or irrigation.

Herbicide			
Common Name	**Trade Name**[a]	**Application Timing**	**Weed Species Controlled**
Glyphosate	Roundup WeatherMax® [25]	Preplant Burndown	Emerged weed species
Paraquat	Gramoxone® [26]		
2,4-D	Agri Star® 2,4-D [37]		
Diclosulam	Strongarm® [110]	PRE[b]	Broadleaf species such as eclipta (*Eclipta prostrata*) and *Amaranthus* spp.
Flumioxazin	Valor® [39]		Broadleaf species such as horseweed (*Conyza canadensis*)
Pendimethalin	Prowl® [40]		Grass and broadleaf species such as foxtail (*Setaria* spp.) and *Amaranthus* spp.
Acifluorfen	Ultra Blazer® [60]	POST[c]	Broadleaf and grass species such as coffee senna (*Senna occidentalis*) and velvetleaf (*Abutilon theophrasti*)
Bentazon	Basagran® [62]		Broadleaf species such as morningglory (*Ipomoea* spp.) and velvetleaf
Chlorimuron	Classic® [75]		Broadleaf weeds such as Florida beggarweed (*Desmodium tortuosum*) and morningglory
Clethodim	Select® [94]		Grass species such as panicum, foxtail, and crabgrass (*Digitaria* spp.)
Imazapic	Cadre® [111]		Broadleaf and grass species such as morningglory, *Amaranthus* spp. and crabgrass
Imazethapyr	Pursuit® [78]		Broadleaf, grass, and sedge species such as Florida pusley (*Richardia scabra*), crabgrass, and nutsedge (*Cyperus* spp.)
Paraquat	Gramoxone®		Grass and broadleaf species
Sethoxydim	Poast® [80]		Grass species, foxtail and panicum
2,4-DB	Butyrac® [112]		Broadleaf species such as velvetleaf and prickly sida (*Sida spinosa*)

[a]Trade names listed are representative of available herbicides. Inclusion of particular trade names does not suggest author endorsement.

[b]PRE, preemergence.

[c]POST, postemergence.

Table 6. Herbicides for use in reduced-tillage peanut.

10. Conclusion

The ever increasing demands on global agriculture dictate the use of intensive, high-yielding production practices. However, the inability to sustain these systems long-term necessitates the implementation of more energy-efficient, environmentally-sound practices that can still produce successful yields. Conservation agriculture practices seek to achieve these goals in order to ensure current and future agricultural production. While components of conservation agriculture, such as reduced-tillage and cover crops, are fundamental practices in these systems, herbicides are still valuable and necessary weed management tools within conservation systems. Integrating these management practices can be challenging and continue to warrant research to identify the most successful means of utilizes herbicides in conjunction with reduced-tillage and cover crops.

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