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Edited by Andrew Price, Jessica Kelton and Lina Sarunaite

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http://dx.doi.org/10.5772/61916
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Notice

First published in Croatia, 2015 by INTECH d.o.o.
eBook (PDF) Published by IN TECH d.o.o.
Place and year of publication of eBook (PDF): Rijeka, 2019.
IntechOpen is the global imprint of IN TECH d.o.o.
Printed in Croatia

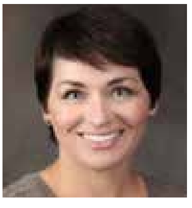
Legal deposit, Croatia: National and University Library in Zagreb

Additional hard and PDF copies can be obtained from orders@intechopen.com

Herbicides, Agronomic Crops and Weed Biology
Edited by Andrew Price, Jessica Kelton and Lina Sarunaite
p. cm.
ISBN 978-953-51-2218-0
eBook (PDF) ISBN 978-953-51-5414-3

Meet the editors

Andrew Price is a weed scientist at USDA-ARS National Soil Dynamics Laboratory as well as an affiliate associate professor at Agronomy and Soils Department, Auburn University. Dr. Price is a native of East Tennessee, USA, and has received both B.S. and M.S. degrees from the University of Tennessee majoring in plant and soil sciences and a Ph.D. from North Carolina State University majoring in crop science. Dr. Price's primary responsibilities in the Conservation Systems Research Group are to conduct research addressing the impact of integrated weed management strategies on weed populations/competitiveness in conservation systems as well as to develop cost-effective and environmentally friendly weed management systems integrating conservation tillage, crop rotations, cover crops, and weed management systems.



Jessica Kelton earned her M.S. degree from Auburn University in agronomy and soils with a concentration in weed science. Mrs. Kelton is a program coordinator in agronomics with the Alabama Cooperative Extension System (ACES), an outreach organization of Auburn University, USA. As a member of the Agronomics Team for ACES, she works in conjunction with other extension personnel to provide farmer education about current production practices to ensure successful grower application of new and ongoing scientific research in agriculture.

Lina Sarunaite is a senior researcher at the Institute of Agriculture, Lithuanian Research Centre for Agriculture and Forestry. Dr. Sarunaite received both B.S. and M.S. degrees from Aleksandras Stulginskis University majoring in agro business and organic agriculture at the Faculty of Agronomy. The topic of her Ph.D. study was "Investigation of ecologically sustainable multifunctional legume-grass swards." After Dr. Sarunaite received a doctoral degree in 2007 at the Institute of Agriculture, LRCAAF, she extended her research to the plant intercrops of various plant combinations in crop rotation, sole crop and its alternative cultivation technologies directed toward effective N utilization, enhancement of crops' competitive power and quality improvement of product, and weed management in sustainable and organic agriculture.

Contents

Preface

Most forms of agriculture depend on integrated pest management strategies, which include herbicides. Herbicide efficacy has contributed to increased food and feed production, improved control of invasive and nonnative weed species, and numerous other benefits for agriculture production as well as consumers. As pest management challenges appear, research is required to improve the uses of herbicide compounds and to further understand the interaction benefits of herbicides in integrated pest management recommendations.

In this book, contributing authors have provided a broad scope of topics related to recent herbicide research. Research detailed in these chapters is focused on herbicides in agricultural settings. Research topics range from herbicide use in lupin, peanut, sesame, and sugar beet to weed biology.

The information provided in this book serves as a valuable tool for describing many areas of current herbicide research affecting agricultural uses. *Herbicides, Agronomic Crops and Weed Biology* should be particularly useful for beginning and established scientists interested in developing research projects focused on understanding new applications of herbicidal compounds and interactions with weed biology. It is hoped that this book will serve the scientific community as a source of current, vital research information to help shape future research and understanding of herbicides.

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Chapter 1

Herbicide-Resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States — Mechanisms of Resistance, Impact, and Management

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M. Jugulam and Amit J. Jhala

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61512

Abstract

Palmer amaranth, a dioecious summer annual species, is one of the most troublesome weeds in the agronomic crop production systems in the United States. In the last two decades, continuous reliance on herbicide(s) with the same mode of action as the sole weed management strategy has resulted in the evolution of herbicide-resistant (HR) weeds, including Palmer amaranth. By 2015, Palmer amaranth biotypes had been confirmed resistant to acetolactate synthase (ALS)-inhibitors, dinitroanilines, glyphosate, hydroxyphenylpyruvate dioxygenase (HPPD)-inhibitors, and triazine herbicides in some parts of the United States along with multiple HR biotypes. Mechanisms of herbicide-resistance in Palmer amaranth are discussed in this chapter. Preplant herbicide options including glufosinate, 2,4-D, and dicamba provide excellent Palmer amaranth control; however, their application is limited before planting crops, which is often not possible due to unfavorable weather conditions. Agricultural biotechnology companies are developing new multiple HR crops that will allow the post-emergence application of respective herbicides for management of HR weeds, including Palmer amaranth. For the effective in-crop management of Palmer amaranth, and to reduce the potential for the evolution of other HR weeds, growers should apply herbicides with different modes of action in tank-mixture and should also incorporate cultural practices including inversion tillage and cover crops along with herbicide programs.

Keywords: Biology, evolution, germination, genetics, integrated management, mechanisms of resistance, physiology, resistance management

1. Introduction

Palmer amaranth (*Amaranthus palmeri* S. Wats.), also known as careless weed, is native to the southwestern United States [1], and is a summer annual belonging to the family Amaranthaceae, which includes around 75 species worldwide [2]. Palmer amaranth leaves and seeds were an important food source in many Native American tribes [3]; when roasted and milled, the seeds of *Amaranthus* spp. are edible and rich in protein, whereas the leaves are high in Ca, Fe, and vitamin A [4,5]. However, Palmer amaranth plants grown under dry conditions can build up nitrate at levels harmful for cattle to consume [6]. Palmer amaranth was historically located in the southern United States; however, human activities in the 20th century—including seed and equipment transportation and agriculture expansion—led to the spread of Palmer amaranth to the northern United States, and it was first reported beyond its original habitat in Virginia in 1915 [7]. In the 1989 annual survey of the Southern Weed Science Society, Palmer amaranth appeared as a troublesome weed in the southern United States [8], and though in 1995 Palmer amaranth was listed as the most troublesome cotton weed in only two southern states (North and South Carolina) [9], by 2009, it was ranked as the most troublesome cotton weed in nine southern states and the second most troublesome weed in soybean [10]. By 2014, Palmer amaranth had become one of the most troublesome and economically important weed species in corn, cotton, and soybean in the United States [10–12].

Palmer amaranth and common waterhemp (*Amaranthus rudis* Sauer) are the only dioecious species (separate male and female plants) of all the pigweeds, whereas redroot pigweed (*Amaranthus retroflexus* L.), smooth pigweed (*Amaranthus hybridus* L.), spiny amaranth (*Amaranthus spinosus* L.), and tumble pigweed (*Amaranthus albus* L.) are monoecious (male and female flowers on the same plant). Palmer amaranth is characterized as a tall (around 2 m long), erect, broadleaf weed with lateral branching. The leaves are hairless, alternate, and lanceolate shaped in young plants and become ovate as plants mature [13]. The upper side of the leaves is often marked with a darker, V-shaped chevron. Palmer amaranth's leaf petiole is as long as or longer than its leaf blade, whereas common waterhemp has a leaf petiole smaller than its leaf blade. The flowers of Palmer amaranth cluster together to form a terminal cylindrical inflorescence, and while the male and female inflorescences look identical, they can be distinguished by touch: the male inflorescence is softer, whereas the female inflorescence is rougher and pricklier. Chromosome number $2n = 34$ as well as chromosome number $2n = 32$ has been reported in Palmer amaranth [14–16].

2. Reproduction biology

As a dioecious species, Palmer amaranth is an obligate outcrosser [17], with pollination occurring by wind. Male plants produce large numbers of pollen seeds with a mean diameter range of 21–38 μm and a mean density of about 1,435 kg m^{-3} [18]. This allows Palmer amaranth pollen to move long distances from the source plant; however, the viability of the pollen is reduced within 30 minutes of anthesis [19]. Previous research has reported the pollen-

http://dx.doi.org/10.5772/61512

mediated transfer of glyphosate-resistant traits from glyphosate-resistant male Palmer amaranth plants to glyphosate-susceptible female plants up to a distance of 300 m [20]. Apparent agamospermy (asexual reproduction or seed production from an unfertilized ovule) was also reported in female Palmer amaranth plants isolated from a pollen source, or in those that had been pollinated by common waterhemp [21,22].

Palmer amaranth plants normally flower during September and October [23]; however, decreasing day lengths hasten the flowering process [24]. Its seeds are smooth, round- or disc shaped, 1–2 mm in diameter [13], and are usually dispersed by gravity. In addition, seed dispersal via irrigation, birds, mammals, plowing, mowing, and harvesting has also been reported in Palmer amaranth [25,26]. Female Palmer amaranth plants are prolific seed producers even under conditions of higher competition in agronomic cropping systems; for example, in North Carolina, Palmer amaranth at densities of 5.2 plants m^{-1} of peanut row produced about 124,000 seeds m^{-2} [27]. In Kansas, Palmer amaranth at densities of 0.5 and 8 plants m^{-1} of corn row produced around 140,000 and 514,000 seeds m^{-2}, respectively [28] (Figure 1). In California, Palmer amaranth plants that emerged between March and June produced more seeds (200,000–600,000 seeds $plant^{-1}$) compared with plants that emerged between July and October ($\leq$ 80,000 seeds $plant^{-1}$) [24] (Figure 2).

Figure 1. A female Palmer amaranth plant in a cornfield in Nebraska, USA. This plant has the capacity to produce more than half a million seeds.

Figure 2. Late-emerging Palmer amaranth plants can also produce seeds later in the season that will add to the soil seed bank.

3. Seed germination

3.1. Temperature

One of the most important environmental factors required for seed germination is the range of temperatures to which seeds are exposed. The optimum temperature range for Palmer amaranth seed germination extends from 25 to 35° C [29]. However, Palmer amaranth seeds showed higher germination at alternating day/night temperatures of 25/20, 30/15, 35/20, 35/0, and 35/25° C compared with constant temperatures of 15, 20, 25, 30, and 35° C, respectively, with no germination at 15/10° C [29,30]. The estimated base temperature (minimum temperature below which phenological development ceases) for Palmer amaranth is 16.6° C, which is higher than other summer annual weeds, including barnyard grass (*Echinochloa crus-galli)*, common purslane (*Portulaca oleracea*), large crabgrass (*Digitaria sanguinalis*), and tumble pigweed [31]. Palmer amaranth seeds showed less dormancy and germinated in a wider range of temperatures when followed by winter after-ripening compared with freshly matured seeds [32]. The induction of secondary dormancy was also reported in Palmer amaranth seeds exposed to high temperatures in summer [32].

3.2. Light

Light plays an important role in breaking dormancy and promoting germination in most of the *Amaranthus* species [33,34]. The quantity of light received by the mother plant has a profound effect on Palmer amaranth seed germination; for instance, the seeds of the female plant grown under full sunlight showed higher germination (25%) in darkness compared with plants that experienced low quantities of light (12%) [32]. Palmer amaranth germination response is partially mediated by phytochrome when followed by after-ripening in the field [32].

3.3. Plant growth hormones

The ratio of abscisic acid (ABA) and gibberellic acid (GA) regulates the physiological dormancy of seeds, with ABA promoting seed dormancy and GA preventing seed dormancy [35–37]. The levels of ABA and GA in seeds are affected by the environmental conditions experienced by the maternal plant during seed development [38,39], and in Palmer amaranth, increased exposure of the mother plants to shade increased the ABA content in seeds, which in turn reduced germination levels in dark conditions and promoted dormancy [40].

3.4. Seed location

The location of the inflorescence on the mother plant as well as the location of the seed within an inflorescence can affect seed germination [36,41]. In Palmer amaranth, 67–78% greater germination was reported from seeds matured in the middle and top third of a female plant than from seeds matured in the bottom third of the plant [40].

3.5. Seed burial depth and duration

The depth and duration of seed burial determine the seed germination, viability, and longevity in the soil. The viability of Palmer amaranth seeds buried at different soil depths (1–40 cm) reduced to < 40% within 3 years of burial; however, more deeply buried seeds showed higher viability than seeds buried at shallow depths [42]. In another study, Palmer amaranth seedlings showed ≥ 35% emergence at burial depths less than 3 cm compared with ≤ 7.2% emergence from seeds buried at depths greater than 5 cm [24].

4. Competitive abilities

4.1. Photosynthesis and growth rate

Growth rate is the chief index of plant competitiveness [43], and Palmer amaranth's aggressive growth habit and prolific seed production make it a serious and problematic weed in agronomic cropping systems [44,45]. Palmer amaranth has the highest plant dry weight, leaf area, height, growth rate (0.10–0.21 cm per growing degree day), and water-use efficiency compared with other pigweeds, including common waterhemp, redroot pigweed, and tumble pigweed

[45,46]. Palmer amaranth plants also respond more positively to higher temperatures and develop more root and shoot biomasses compared with common waterhemp and redroot pigweed [29,47,48].

Different physiological and morphological characteristics contribute to the greater growth of Palmer amaranth even under water stress conditions. Under high soil water availability, Palmer amaranth has a high photosynthetic capacity (80 μmol CO_2 m^{-2} s^{-1}) and its photosynthesis is not light saturated (except at a lower leaf water potential of −2.9 MPa) at an irradiance level of 400–700 nm [49]. In addition, Palmer amaranth leaves can orient themselves perpendicular to incoming sunlight (diaheliotropism), allowing the plant to take advantage of its high photosynthetic capacity [50]. High photosynthetic rates along with diaheliotropic movement allow the plant to fix carbon at faster rates, promoting more aggressive growth. Although conditions of prolonged drought can decrease leaf water potentials in most plants, resulting in closure of the stomata during the day, Palmer amaranth can respond to lower leaf water potentials by increasing its leaf solute concentration, allowing the stomata to remain open longer during periods of drought [51].

Shading causes a detrimental effect on plant growth by reducing the quality, quantity, and intensity of photosynthetic active radiations (PAR) [52–54]. C3 weed species can adapt better to lower light conditions [55,56] compared with C4 species that are better adapted to higher irradiance levels [54,57]. However, Palmer amaranth plants have also reported adapting to reduced irradiance levels by lowering their light compensation and leaf and main-stem branch appearance rates, or by increasing their total leaf chlorophyll, leaf dark respiration, and specific leaf area [58].

4.2. Root morphology

Palmer amaranth has a deep and fibrous root system with a root to shoot biomass ratio of 0.16 ± 0.02 [59]. Palmer amaranth roots are finer, longer, and greater in number compared with soybean with a similar root fresh weight [48]. This root morphology enables Palmer amaranth to occupy a much larger soil volume and gain a competitive advantage over other crops in the acquisition of nutrients, especially during conditions of drought and low fertility. Palmer amaranth roots can penetrate highly compact soils and are more efficient in their nitrogen uptake compared with soybean genotypes [60]. In addition, Palmer amaranth can maintain stable overall shoot and root growth when downward root growth becomes restricted due to the compact soil or hard pans commonly found in Piedmont and coastal plain soils [60].

4.3. Allelopathy

Palmer amaranth, along with other *Amaranthus* species, exerts allelopathic effects on several crops and weeds [61–63]. Menges [61] reported that soil-incorporated residues of Palmer amaranth inhibited carrot (*Daucus carota* L.) and onion (*Allium cepa* L.) growth by 49% and 68%, respectively. Among the soil-incorporated residues, thyrsus (inflorescence) and leaf tissues caused more seedling damage in carrot, onion, cabbage (*Brassica oleracea* var. *capitata* L.), and sorghum (*Sorghum bicolor* L. Moench.) compared with the stems and roots of Palmer amaranth [62].

4.4. Host to plant bugs and nematodes

Palmer amaranth is an important host for tarnished plant bugs, a major pest of cotton in the midsouthern United States, and is also a host for nematodes in tobacco [64]. Crop rotation from susceptible host crop to non-host crop is an effective nematode management strategy; however, Palmer amaranth's presence during the non-host crop season reduced the benefits of crop rotation.

4.5. Seed herbivory

Palmer amaranth seeds make up a food source for various animals, birds, and insects. Sosnoskie et al. [42] reported Palmer amaranth seed removal by rodents from seed traps, though the percentage of seed consumption is unknown. Palmer amaranth seeds are also consumed by birds such as killdeer (*Charadrius vociferus*) and mallard ducks (*Anas platyrhynch*), remaining viable even after passing through their intestinal tracts. This viability allows these birds to serve as a vector for Palmer amaranth seed dispersal across long distances [65].

5. Crop yield losses

The widespread adoption of no-tillage systems, reduced reliance on soil-applied residual herbicides, and increased herbicide resistance have contributed toward the increased infestation of Palmer amaranth in different cropping systems [45,66,67].

5.1. Cotton

Palmer amaranth's season-long interference in cotton at densities of 10 plants per 9.1 m^2 area reduced cotton canopy volume, biomass, and yield by 45%, 50–54%, and 54%, respectively; however, cotton canopy height and lint properties were not affected [68]. In another study, 6–11.5% cotton yield reduction was reported with each Palmer amaranth plant in 9.1 m^2 area [69]. In addition to yield reduction, Palmer amaranth interferes during cotton harvesting operations and increases harvest time by two- to threefold compared with weed-free control [70]. The presence of Palmer amaranth during cotton harvesting often causes cotton lint contamination, thus increasing lint-cleaning requirements, adding to the cost of production [70].

5.2. Soybean

Development of a dense and early-season canopy makes soybean more competitive to weed pressure compared with cotton [71]. However, soybean yield reduction ranging from 17% to 68% was reported in Arkansas at Palmer amaranth densities of 0.33–10 plants m^{-1} of row [72]. In Kansas, soybean yield reduction of about 78%, 56%, and 38% was reported by Palmer amaranth, common waterhemp, and redroot pigweed, respectively, at an individual density of 8 plants m^{-2} [73]. Early-emerging Palmer amaranth plants also cause more soybean grain yield loss compared with later-emerging plants [73].

5.3. Corn

Palmer amaranth plants that emerged along with corn caused higher corn grain yield losses (11–91%) compared with plants emerging later than corn (7–35%) at the same densities of 0.5–8 plants m^{-1} of row, respectively [28]. Palmer amaranth at densities of 0.5–8 plants m^{-1} of cornrow caused 1–44% corn forage yield loss, respectively [74], and under dryland production systems, Palmer amaranth at 1–6 plants m^{-1} of cornrow also resulted in 18–38% corn grain yield loss [75].

5.4. Peanut

Palmer amaranth plants outgrow peanut (*Arachis hypogaea* L.) and interfere with growth and harvesting operations. Palmer amaranth decreased the canopy diameter of peanut and caused between 28% and 68% yield loss at densities of 1 and 5 plants m^{-1} of peanut row, respectively [27].

5.5. Sorghum

Palmer amaranth at 1.58 plants m^{-2} was reported to cause 38–63% sorghum grain yield loss [76], and in addition, Palmer amaranth infestation increased sorghum grain moisture content, thus delaying harvesting operations.

6. Evolution of herbicide-resistance in Palmer amaranth

One of the inevitable consequences of the repeated use of single mode-of-action herbicides as a primary weed control strategy is the selection of weeds resistant to that particular herbicide. To date, a total of 245 species are confirmed resistant to 22 of the 25 known mode-of-action herbicides [77]. In addition, weeds can evolve resistance to multiple herbicides through sequential selection [78]. Prolonged and repeated use of herbicides with different modes of action resulted in the evolution of multiple herbicide-resistant Palmer amaranth populations in several parts of the United States [79]. Palmer amaranth is one of the few weeds in the United States that have evolved resistance to multiple modes of action herbicides (e.g. microtubule-, photosystem (PS) II-, acetolactate synthase (ALS)-, 5-enol-pyruvylshikimate-3-phosphate synthase (EPSPS)-, and hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors) [77]. Consequently, the infestation of multiple herbicide-resistant Palmer amaranth populations remains a serious threat to agriculture throughout the United States as no herbicides with new sites- or modes of action have been commercialized in the past two decades [80].

Weed resistance against herbicides can be conferred either by (a) target site resistance (TSR) and/or (b) non-target site resistance (NTSR) mechanisms. TSR mechanisms largely involve mutation(s) in the target site of action of an herbicide, resulting in an insensitive or less sensitive target protein for the herbicide [78]. In such cases, the TSR is determined by monogenic traits [81]. In addition, weeds can evolve TSR as a result of overexpression or amplification of the target gene [82]. On the other hand, NTSR mechanisms include reduced herbicide uptake/translocation, increased herbicide detoxification, decreased herbicide activation rates, and/or herbicide sequestration [83]. Metabolism-based NTSR involves increasing the activity of enzyme complexes such as esterases, cytochrome P450s, glutathione *S*-transferases (GSTs), and/or UDP-glucosyl transferases [78]. NTSR—especially if it involves herbicide detoxification by these enzymes—is usually governed by many genes (polygenic) and may confer resistance to herbicides with completely different modes of action [81,84]. Evolution of NTSR via means of herbicide detoxification is a serious threat to weed management, as it can bestow resistance to multiple herbicides, leaving growers with limited herbicide options for weed control as well as granting weeds with potential resistance to herbicides not yet commercially available [85]. Furthermore, it has been proposed that low herbicide doses result in the evolution of polygenic traits, whereas high herbicide doses may favor monogenic target site-based resistances [86–88].

7. Mechanisms of herbicide-resistance in Palmer amaranth

As indicated above, Palmer amaranth populations have evolved resistance to at least five modes of action of herbicides: microtubule-, PSII-, ALS-, EPSPS-, and HPPD-inhibitors. Some Palmer amaranth populations across the United States have also been found resistant to more than two mode-of-action herbicides [77].

7.1. Resistance to microtubule assembly-inhibitors in Palmer amaranth

Microtubules are important components during cell division that help chromosome movement during the anaphase of the cell cycle. Microtubules are long cylindrical molecules made up of protein, and tubulin. Some herbicides, such as trifluralin, inhibit microtubule formation during cell division, resulting in cessation of growth in meristematic regions. Palmer amaranth resistant to trifluralin was reported as early as 1989 and 1998 in the United States in South Carolina and Tennessee, respectively; however, the mechanism of resistance is unknown. The Palmer amaranth population from South Carolina is also cross-resistant to other dinitroaniline herbicides such as benefin, isopropalin, pendimethalin, and ethalfluralin [89].

7.2. Resistance to PSII inhibitors in Palmer amaranth

PSII inhibitors (e.g. atrazine, simazine, bromoxynil, etc.) are among the most popular and widely used herbicides, and have been in use in corn and grain sorghum for several decades. PSII inhibitors compete for the plastoquinone-binding site in the electron transport chain in PSII; this inhibits electron flow in the light reaction of photosynthesis, resulting in depletion of reducing power (NADPH) and ATP synthesis, which are required for the Calvin cycle. Atrazine resistance in the majority of weeds was reported to be due to nucleotide substitution in the *psbA* gene that encodes D1 protein in PSII (the target site of atrazine in the chloroplast) and hence is maternally inherited. PSII inhibitor resistance in Palmer amaranth was first documented in 1993 in Texas and thereafter reported in other states, namely, Kansas (1995), Georgia (2008), and Nebraska (2011) [77]. Although the mechanism of resistance to atrazine in

Amaranthus species such as waterhemp [90] and *Amaranthus powelli* [91] is reported as Ser-264 to Gly substitution in the *psb*A gene, the mechanism of resistance to PSII inhibitors in Palmer amaranth is not known.

7.3. ALS inhibitor resistance in Palmer amaranth

ALS-inhibitors inhibit the ALS enzyme, which is required for the biosynthesis of branched-chain amino acids valine, leucine, and isoleucine. ALS-inhibitor resistance in Palmer amaranth is widespread across the United States [77], and many Palmer amaranth populations also exhibit cross-resistance to several ALS-inhibiting herbicides. For example, imazethapyr-resistant Palmer amaranth from Kansas was found to be approximately 2,800 times more resistant to imazethapyr compared with the sensitive biotype, with the population also cross-resistant to the sulfonylurea herbicides such as thifensulfuron and chlorimuron. ALS enzyme inhibition assays suggest the presence of an insensitive ALS enzyme, possibly because of a target-site mutation [92] in this population. Similarly, imizaquin-resistant Palmer amaranth from Arkansas is also cross-resistant to chlorimuron, diclosulam, and pyrithiobac [93]. Although the specific mutation/s contributing to the resistance of imidazolinone/sulfonylurea herbicides in Palmer amaranth is unknown, in other *Amaranthus* species such as waterhemp and smooth pigweed, mutations in the ALS gene at amino acid positions W574 (tryptophan) or S653 (serine) [94] and A122 (alanine), A205 (alanine), D376 (aspartate), W574 (tryptophan), or S653 (serine) [95], respectively, are known to confer ALS-inhibitor resistance.

7.4. Glyphosate-resistance in Palmer amaranth

Glyphosate is the most widely used agricultural pesticide globally and it is used extensively in Roundup Ready corn, cotton, and soybean crops in the Midwestern United States. Glyphosate inhibits EPSPS enzyme synthesis in plants, thus preventing the biosynthesis of the aromatic amino acids phenylalanine, tyrosine, and tryptophan, and resulting in the death of glyphosate-sensitive plants. Glyphosate resistance in Palmer amaranth was first documented in 2004 in Georgia [96], and since then Palmer amaranth populations resistant to glyphosate have been documented in several U.S. states [77]. Glyphosate resistance in Palmer amaranth is conferred by two mechanisms: TSR due to EPSPS gene amplification, and NTSR through reduced absorption and translocation of glyphosate. These resistance mechanisms evolved independently at two locations due to intense glyphosate use in Roundup Ready cropping systems. The mechanism of resistance in Georgia Palmer amaranth populations was investigated, and for the first time it was found that resistant plants have increased *EPSPS* gene copies (> 100 copies), which are distributed throughout the genome. The EPSPS copies are also functionally correlated to the increase in enzyme expression to resist high rates of glyphosate [97]. EPSPS gene amplification as the mechanism of glyphosate resistance was also reported in Palmer amaranth populations from North Carolina [98,99], Mississippi [100], and New Mexico [101], whereas low levels of resistance to glyphosate because of reduced uptake and translocation were reported in Palmer amaranth populations from Tennessee [102] and Mississippi [103].

7.5. HPPD inhibitor-resistance in Palmer amaranth

Both PSII- and HPPD-inhibitor (e.g. mesotrione, tembotrione, pyrasulfotole) herbicides are used mostly as premixes, although it is not uncommon to use them alone. HPPD-inhibitors primarily inhibit carotenoid and tocopherol biosynthesis in plants [104]. In photosynthesis, carotenoids protect chlorophyll from photo-oxidation that occurs due to the formation of triplet chlorophyll and singlet oxygen [104]. Ultimately, sensitive species will die because of lipid peroxidation, leading to membrane destruction. HPPD-inhibiting herbicides are effective management tools for controlling glyphosate-, triazine-, and ALS-inhibitor-resistant Palmer amaranth populations in corn and grain sorghum; however, some Palmer amaranth biotypes were not controlled following treatment with pyrasulfotole and bromoxynil (formulated in 1:8 ratio in Huskie®) in central Kansas [105]. Paradoxically, this particular field had no previous history of HPPD-inhibitor herbicide use. This Palmer amaranth biotype was 7–11 times more resistant to premixes of pyrosulfotole and bromoxynil than susceptible biotypes were [105]. Furthermore, inheritance studies suggested that the HPPD-resistant trait in this population is transmitted via pollen. To date, HPPD-inhibitor resistance has been reported in only two weed species; *viz*., Palmer amaranth and waterhemp, although from several Midwestern states (Kansas, Nebraska, Illinois, and Iowa) [77]. It is highly likely that HPPD-inhibitor resistance may spread via pollen or seed to other regions and possibly into other related species through pollen-mediated interspecific hybridization [17,106]. Experiments are in progress to determine the mechanism of HPPD-inhibitor resistance in this Palmer amaranth biotype.

8. Management of Palmer amaranth

8.1. Chemical control

Herbicide-resistant Palmer amaranth management with herbicides should involve herbicides with different modes of action. An ideal management program should start with a preplant burndown treatment followed by a PRE residual herbicide, and one or two POST herbicide applications. It is also recommended to tank-mix POST treatments with a residual herbicide to prevent Palmer amaranth emergence later in the growing season.

8.1.1. Corn

Several PRE corn herbicides containing single or multiple active ingredients including acetochlor, alachlor, atrazine, dimethenamid-*P*, flumioxazin, fluthiacet-methyl, isoxaflutole, mesotrione, pyroxasulfone, *S*-metolachlor, and saflufenacil can effectively control emerging Palmer amaranth resistant to both ALS-inhibitors and glyphosate [107,108]. Palmer amaranth 16–20 plants m^{-2} was controlled 95%, 78%, and 44% with acetochlor, atrazine, and flufenacet plus isoxaflutole, respectively, at 10–12 weeks after planting [109]. Palmer amaranth at moderate densities (8–10 plants m^{-2}) was controlled at least 97% with acetochlor, atrazine, and flufenacet plus isoxaflutole [109].

There are multiple POST herbicide options for controlling Palmer amaranth resistant to both ALS-inhibitors and glyphosate in glyphosate-tolerant corn. Commonly used POST herbicides may contain one or more active ingredients from growth regulators (2, 4-D, dicamba, and diflufenzopyr), HPPD inhibitors (mesotrione, tembotrone, and topramezone), and PS II inhibitors (atrazine) [107]. Of these POST herbicides, 2, 4-D and dicamba provide only POST activity, whereas atrazine, mesotrione, tembotrione, and topramezone can provide both PRE and POST control of Palmer amaranth. If the herbicide label allows tank mixing, a residual herbicide such as acetochlor or *S*-metolachlor should be combined with a POST herbicide to prevent Palmer amaranth emergence later in the season. Another viable alternative is planting a glufosinate-tolerant (LibertyLink® trait) variety of corn and using glufosinate with labeled POST tank-mix partners.

8.1.2. Cotton

An ideal herbicide program for controlling herbicide-resistant Palmer amaranth in cotton should begin with tillage or a preplant burndown treatment containing a residual herbicide to produce a clean start [110,111]. For small (≤ 10 cm) emerged Palmer amaranth seedlings, glufosinate or paraquat can be used in tank-mixture with a residual herbicide such as flumioxazin or diuron at or prior to planting [7,112–115]. When flumioxazin is used in a burndown program, depending upon the flumioxazin rate used, cotton planting should be delayed 15–21 days after burndown treatment in a no-till system and 30 days in a conventional tillage system to prevent cotton injury.

The preplant burndown treatment should be followed by a residual PRE treatment. Several residual PRE herbicides including diuron, flumeturon, fomesafen, pendimethalin, and prometryn can be used to achieve early-season control of Palmer amaranth resistant to ALS-inhibitors, glyphosate, or both [115–118,115]. Pyrithiobac, an ALS-inhibitor herbicide, may be used PRE for controlling glyphosate-resistant Palmer amaranth, though it will not control ALS-resistant populations. Research conducted in Alabama reported 90% Palmer amaranth control at 6 weeks after treatment with PRE application of pendimethalin plus fomesafen [119]. In North Carolina, flumeturon or pendimethalin PRE-alone programs failed to provide adequate (< 60%) control of Palmer amaranth late in the season [120]. Flumeturon was reported less effective on Palmer amaranth than diuron or fomesafen in studies conducted in Georgia and North Carolina [121], and in another study, pyrithiobac (71 g ha^{-1}) applied as preplant incorporation (PPI) or PRE controlled Palmer amaranth ≥ 97% at 6 weeks after treatment [122]. Research conducted at the University of Georgia recommended a PRE program consisting of tank mixing two herbicides out of acetochlor, diuron, and fomesafen [110]. However, the effectiveness of these PRE herbicides is quite variable and depends upon timely activation by rain or irrigation.

Unfortunately, limited POST herbicide options are available for controlling glyphosate-resistant Palmer amaranth in glyphosate-resistant cotton. Pyrithiobac and trifloxysulfuron applied POST can control small (≤ 10 cm) Palmer amaranth [122–124]; however, Palmer amaranth control with pyrithiobac applied POST may vary depending upon environmental conditions [122]. In previous studies, pyrithiobac and trifloxysulfuron caused significant cotton injury (35%); however, the injury was transitory and did not affect the yield [124–128].

POST herbicides such as diuron, fluometuron, and prometryn can be tank-mixed with MSMA (monosodium methyl arsenate) for Palmer amaranth control in both transgenic and non-transgenic cotton. These herbicides can control small and newly emerged weeds, and provide residual control [124,129,130]. However, growers often miss the height differential period necessary for POST application because of Palmer amaranth's rapid growth rate [45]. In addition, POST herbicides may injure cotton and often adversely affect cotton maturity and yield [131,132].

Research conducted in the southern United States recommended one to two follow-up tank-mixed applications of a residual herbicide such as pyrithiobac or *S*-metolachlor, and a POST herbicide such as glyphosate in glyphosate-tolerant cotton or glufosinate in glufosinate-tolerant cotton for Palmer amaranth control [110,117,119]. However, glyphosate and pyrithiobac tank-mixed applications will not be a viable option for controlling Palmer amaranth resistant to both ALS-inhibitor and glyphosate. Therefore, for controlling Palmer amaranth resistant to both ALS-inhibitors and glyphosate, planting glufosinate-tolerant cotton and using glufosinate tank-mixed with pyrithiobac and/or *S*-metolachlor as POST application will be an effective POST management strategy. Finally, a POST-directed lay-by application of diuron or prometryn plus MSMA made no later than first bloom cotton stage would control the late-emerged Palmer amaranth and also ensure a clean field later in the season [110,117].

8.1.3. Soybean

Before the evolution of glyphosate-resistance, Palmer amaranth populations—including those resistant to ALS-Inhibitor herbicides—were effectively managed by glyphosate in glyphosate-tolerant crops [123,133,134]. Currently, glyphosate-resistant Palmer amaranth interferes with soybean production in more than 22 states in the United States [77]. To manage Palmer amaranth resistant to ALS-inhibitors and glyphosate, it is necessary to start clean with a preplant burndown treatment using an herbicide such as 2,4-D, carfentrazone, dicamba, glufosinate, or paraquat [118,135]. To prevent early season Palmer amaranth emergence, a residual herbicide such as flumioxazin or saflufenacil can be tank-mixed with 2, 4-D or dicamba burndown treatment [114]. Soybean planting intervals of at least 21 days must be maintained after burndown application of 2, 4-D (0.56 kg ae ha^{-1}) or dicamba (0.28 kg ae ha^{-1}) to avoid significant soybean injury [136].

Herbicides labeled for PRE control of glyphosate-resistant Palmer amaranth may contain one or more of the five different site-of-action groups: ALS-inhibitors (chlorimuron, imazaquin, and imazethapyr), long-chain fatty acid inhibitors (acetochlor, alachlor, dimethenamid-*P*, pyroxasulfone, and *S*-metolachlor), microtubule inhibitors (pendimethalin and trifluralin), PPO-inhibitors (flumioxazin, fomesafen, saflufenacil, and sulfentrazone), and photosystem II (PS II)-inhibitors (linuron and metribuzin), all of which can effectively prevent glyphosate-resistant Palmer amaranth emergence [116, 117,137, 138, 107, 118, 108]. When properly activated by timely rainfall or irrigation, residual PRE herbicides can provide 2–3 weeks of Palmer amaranth control depending on soil moisture and weed pressure. However, in fields where Palmer amaranth is resistant to both ALS-inhibitors and glyphosate, herbicides with an ALS-inhibitor site of action will not be effective in controlling it. Research conducted in North Carolina reported that *S*-metolachlor was more effective than pendimethalin, and that flumioxazin and fomesafen were more effective than metribuzin plus chlorimuron in controlling glyphosate-resistant Palmer amaranth [139].

Contemporary POST herbicides labeled for glyphosate-resistant Palmer amaranth control in glyphosate-resistant soybean belong to two sites of action groups: ALS-inhibitors (thifensulfuron, imazamox, imazaquin, and imazethapyr) and PPO-inhibitors (acifluorfen, fomesafen, and lactofen) [135,107]. In non-sulfonylurea-tolerant (ST) soybean varieties, a premix of chlorimuron plus thifensulfuron at 26.5 g ha^{-1} can control ≤ 10-cm-tall Palmer amaranth; however, in ST soybean varieties, higher rates (80 g ha^{-1}) can be used to control 20-cm-tall plants. In a North Carolina study, > 80% late-season control of glyphosate-resistant Palmer amaranth was achieved with pendimethalin/*S*-metolachlor plus flumioxazin; fomesafen/metribuzin plus chlorimuron applied PRE followed by a POST application of fomesafen [139].

Palmer amaranth populations resistant to ALS-inhibitors can be effectively managed with POST applications of glyphosate in glyphosate-tolerant production systems. Early-POST application of PPO-inhibitors is the only POST option for control of Palmer amaranth resistant to both ALS-inhibitors and glyphosate in glyphosate-tolerant soybean. However, Palmer amaranth control with PPO-inhibitors is highly variable depending on weed size and environmental conditions. PPO-inhibitors are contact herbicides and would not adequately control Palmer amaranth > 10 cm tall. It is strongly recommended to tank- mix the POST treatment with a residual herbicide such as acetochlor, dimethenamid-*P*, pyroxasulfone, or *S*-metolachlor to prevent Palmer amaranth emergence later in the season. As of 2015, no Palmer amaranth population resistant to PPO-inhibitors has been reported [77]; however, sole reliance on PPO-herbicides as a POST-only option will likely result in selection for Palmer amaranth biotypes resistant to PPO-inhibitor herbicides. Ideally, PPO-inhibitor herbicides should be used once per growing season as a PRE or POST treatment along with a residual herbicide containing a different mode of action to ensure long-term sustainability.

An alternate option for POST control of glyphosate-resistant Palmer amaranth is planting glufosinate-tolerant soybean and using glufosinate POST tank -mixed with acetochlor, pyroxasulfone, or *S*-metolachlor to control the Palmer amaranth that has already emerged while further preventing late-season emergence [137]. Additionally, glufosinate will not control Palmer amaranth > 10 cm in size. In a Nebraska study, excellent season-long control of common waterhemp was achieved with sulfentrazone plus metribuzin applied PRE followed by early POST application of glufosinate tank -mixed with acetochlor, pyroxasulfone, or *S*-metolachlor [137].

8.2. Non-chemical control

The principal non-chemical options for Palmer amaranth management involve the use of tillage and cover crops. Tillage can alter weed seedling emergence patterns by modifying seed burial depth, dormancy, predation, and mortality. Furthermore, tillage modifies the environmental factors crucial for germination, such as temperature, moisture, and oxygen [140–142].

In conservation agriculture, weed seed germination is often higher because most of the weed seeds lie on the soil surface where germination conditions are more favorable [143–146]. Therefore, small-seeded weed species such as Palmer amaranth have become highly prevalent in reduced tillage production systems [147]. As Palmer amaranth seedlings cannot emerge from depths ≥ 5 cm, tillage systems that bury seeds deeper than 5 cm can reduce Palmer amaranth densities to levels easily controlled by a PRE or POST herbicide [117,119]. A moldboard plow can bury Palmer amaranth seeds at least 10 cm deep and provides around 50% control of Palmer amaranth [148]. Another study reported ≥ 75% reduction in Palmer amaranth densities with the use of inversion tillage in cotton [119], while sweep cultivators further improved Palmer amaranth control with PRE herbicides in cotton [149]. Spring tillage that included two passes of a disk cultivator or one pass of a disk cultivator followed by one pass of a field cultivator/chisel plow reduced Palmer amaranth densities by 40% compared with no-tillage [119]. In the same study, following inversion tillage, spring tillage did not improve Palmer amaranth control.

Cover crops control weeds by reducing early-season weed density as a result of direct competition from cover crop biomass [150–156] or allelopathy [157–160]. Palmer amaranth was controlled 78–90% by various cover crops when evaluated at the four-node stage of cotton in Arkansas [161]. In the same study, a cereal rye cover crop that produced 846 g biomass m^{-2} controlled Palmer amaranth by 90%. In Alabama, cereal rye cover crop reduced early-season Palmer amaranth density more than 60% compared with conventional tillage and winter fallow systems [162]. Similarly, crimson clover and cereal rye cover reduced Palmer amaranth density by > 50% in cotton [117,119], whereas Price et al. [163,164] and Saini et al. [165] reported similar reductions in Palmer amaranth and other weed densities by cover crop residues.

When cover crops were combined with fall inversion tillage, Palmer amaranth density was reduced by > 85% [117,166]. Cereal rye cover following deep tillage in the fall increased control by 18% when used in conjunction with a glufosinate-based cotton herbicide program [167]. In addition, allelochemicals produced by cereal rye can inhibit Palmer amaranth germination and seedling growth [159].

Evidently, tillage systems and cover crops can significantly reduce Palmer amaranth emergence, but considering Palmer amaranth's high seed production potential (600,000 seeds plant $^{-1}$), reduction in densities as high as 99% may not warrant the long-term validity of a control tactic. The ideal approach for Palmer amaranth management must embrace a zero-tolerance strategy (100% control) for year-round management of Palmer amaranth on a long-term basis. Nevertheless, the potential for reducing weed emergence should encourage the use of appropriate tillage systems and cover crops in an integrated weed management approach for early-season suppression of Palmer amaranth.

9. Multiple herbicide-resistant crop technologies

Multiple herbicide-resistant corn, cotton, and soybean cultivars have recently been developed using molecular techniques for addressing the growing need to control glyphosate-resistant weeds. The major developments in herbicide-resistant technologies include the Enlist™ weed control system and the Roundup Ready Plus Xtend system in corn, cotton, and soybean.

9.1. Enlist Duo™ weed management system

The Enlist Duo™ weed control system will be applicable in all Enlist™ crops (corn, cotton, and soybean) containing traits that make them tolerant to 2,4-D as well as glyphosate. Enlist™ corn will also be tolerant to the grass herbicides belonging to the aryloxyphenoxy propionate family that contain quizalofop, fluazifop, etc. In addition, Enlist™ corn, cotton, and soybean will also be tolerant to glufosinate.

The Enlist Duo™ herbicide contains glyphosate and 2,4-D choline, a low-volatile formulation of 2,4-D manufactured using Colex-D™ technology. The spectrum of weed control with the Enlist™ system will be similar to glyphosate plus 2,4-D. In corn, the new system will provide flexibility in applying this tank-mixture up to the V8 growth stage or 76 cm height. In cotton and soybean, the Enlist Duo™ system will enable POST application of 2,4-D choline to manage glyphosate-resistant broadleaf and other difficult-to-control weeds. Enlist™ soybean can receive POST applications of Enlist Duo™ herbicide up to the R2 or full-flower stage of soybean. The new seed traits (Enlist™ Corn and Soybean) and the new herbicide premix (Enlist Duo™) have recently been deregulated by the United States Department of Agriculture (USDA) and the United States Environmental Protection Agency (USEPA), respectively.

9.2. Roundup Ready® 2 Xtend weed management system

The Roundup Ready® 2 Xtend weed management system is being developed in corn, cotton, and soybean based on Roundup Ready 2 Xtend™ seed traits that make them tolerant to both glyphosate and dicamba. The Roundup® Xtend herbicide, a premix of glyphosate and dicamba, will provide an additional tool for controlling troublesome weeds, including those resistant to glyphosate. The new formulation of dicamba integrated into the Roundup® Xtend herbicide has been claimed to be significantly less volatile than existing formulations of dicamba based on VaporGrip™ Technology. The dicamba component amenable with the Roundup® Xtend weed management system will also be available separately as Xtendimax to allow growers to apply it with labeled tank-mix partners in addition to glyphosate.

The new traits will be marketed as Roundup Ready 2 Xtend soybeans and Bollgard II Xtend Flex cotton. The Roundup® Xtend herbicide may be applied up to 7 days before harvest in cotton and up to the R1 or flower-initiation stage of soybean. Previous researchers have reported excellent control of glyphosate-resistant weeds when dicamba was used alone or combined with glyphosate [168–171].

These technologies will offer growers the flexibility to control weeds, allow for the continued use and adoption of reduced tillage practices, and will help reduce the risk of selecting glyphosate-resistant weeds. The main concern about these technologies is off-target movement via particle drift or volatility that can severely damage sensitive crops such as tomato, grape, melons, and nursery plants as well as the agronomic crops that are not tolerant to 2,4-D or dicamba [172]. Although the new formulations of both 2, 4-D and dicamba are claimed to be far less volatile than traditional chemistries, the manufacturers of these traits are also developing application technologies to minimize the drift potential.

Other herbicide-resistant technologies include MGI soybean™, which will be tolerant to mesotrione, glufosinate, and Isoxaflutole, and Balance Bean tolerant to Isoxaflutole [173]. The latest version of Balance GT™ soybeans carries traits for tolerance to either glyphosate and isoxaflutole, or the latter plus glufosinate. It is widely believed that the HPPD component will probably be applied PRE followed by glyphosate/glufosinate or other POST herbicides. Both MGI soybean and Balance Bean traits will broaden the herbicide options for soybean growers for resistant weed management; however, their commercial cultivation is pending approval by federal government agencies.

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Chapter 2

Sesame (*Sesamum indicum*) Response to Postemergence-directed Herbicide Applications

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61554

Abstract

Field studies were conducted from 2006 to 2010 under weed-free conditions in south Texas and in the Texas High Plains to determine sesame tolerance to applied postemergence-directed herbicides. Injury was greatest when herbicides were applied to 15 cm of the main stem compared to herbicide applications made to 5 cm of the main stem height. Glyphosate at 0.84 kg ae/ha and pyrithiobac-sodium at 0.07 kg ai/ha resulted in the greatest sesame stunting (28–90%) when applied up to 15 cm main stem height, while carfentrazone-ethyl, flumioxazin, and imazethapyr caused greatest injury when applied to 5 cm of the main stem. When glyphosate was applied up to 5 cm main stem height, sesame injury was 20% or less. Glyphosate applied up to the 15 cm stem height and pyrithiobac-sodium applied 5 and 15 cm stem height consistently reduced sesame yield when compared with the nontreated control. Acetochlor, diuron, fluometuron, and prometryn did not cause any sesame stunting. Carfentrazone-ethyl, diuron, flumioxazin, imazethapyr, propazine, pyraflufen-ethyl, linuron, and linuron plus diuron reduced sesame yield in at least one year in south Texas.

Keywords: Injury, *Sesamum indicum*, sesame, growth, yield

1. Introduction

Sesame (*Sesamum indicum* L.) is one of the oldest crops known to humans. There are archeological remnants of sesame dating to 5500 BC in the Harappa Valley in the Indian subcontinent [1]. Assyrian tablets from 4300 BC describe how before the gods battled to restore order to the universe, they ate bread and drank sesame wine [2]. Sesame was a major oilseed in the ancient world because of its ease of extraction, great stability, and drought resistance. Sesame production and consumption has been increasing dramatically in the last decade as emerging countries such as China, Korea, and India utilize more sesame based on traditional uses, and thus more is known in these regions about the positive health attributes of this crop. Incidentally, China has changed from being the largest exporter of sesame to the largest importer and India is close to transitioning from the second largest exporter to a net importer. With regard to the health effects, Bedigian [3] has edited a collection of past plus recent research that shows that minor compounds such as lignans "confer outstanding resistance to oxidation and cancer and depress blood pressure and cholesterol levels."

Previous papers [4,5,6,7] have described the problems associated with sesame and weed control as summarized below.

a. Sesame seeds are small and produce a small cotyledon, while many weeds have a larger cotyledon and accelerate their growth faster than sesame.

b. Sesame growth is very slow in the first 4 weeks (wks) after planting (Figure 1), allowing many weeds to grow taller and shade out the sesame as well as use soil moisture and nutrients [8]. Species of *Amaranthus* can be 3 to 4 times taller than sesame in the first 3 wks after planting.

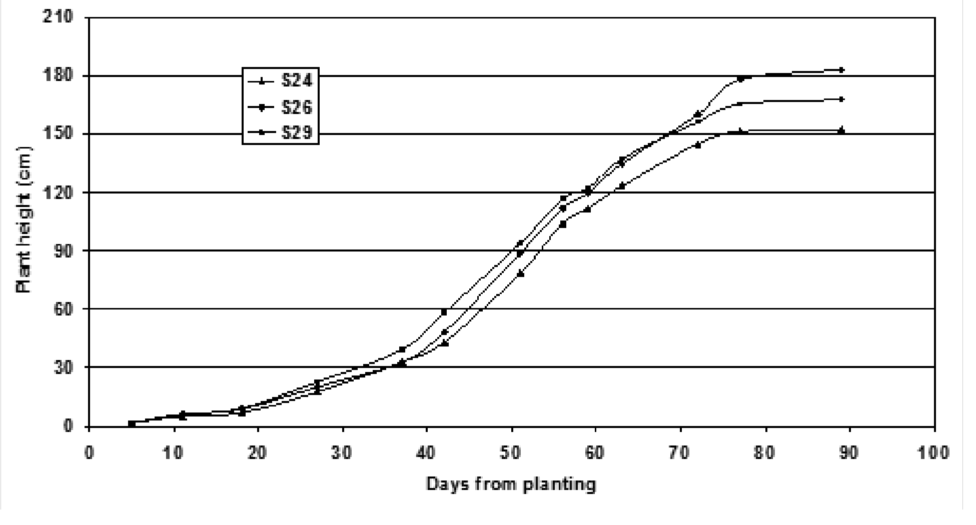

Figure 1. Sesame growth as influenced by days after planting.

c. The presence of weeds can negatively influence sesame yield. Kropff and Spitters [9] reported that the major factor influencing sesame yield loss in a competitive situation between the crop and weed is the ratio between the relative leaf area of the weed and the crop at the time of canopy closure. The effects of weeds on sesame establishment and growth have been well documented. Balyan [10], Gurnah [11], Singh et al. [12], and Upadhyay [13] reported weed-induced reductions of sesame yield up to 100% and a need for a critical weed-free period up to 50 days (d) after planting. Under weedy conditions, Eagleton et al. [14] recorded a weed biomass 6 times that of sesame 48 d after planting and Bennett [15] reported a weed biomass 1.3-fold that of sesame 42 d after planting. Mahgoub

http://dx.doi.org/10.5772/61554

et al. [16] compared weedy and weed-free plots of sesame and the effect of weeds on sesame yield over time (Figure 2). The critical period of weed control is the time interval where control is essential to avoid a yield loss and is the interval between the length of weed competition tolerated and the weed-free requirement [17]. In peanut (*Arachis hypogaea* L.), Hill and Santelmann [18] reported that yields were not influenced by weeds removed as late as 3 wks after planting and weed control must persist for at least 6 wks after planting to better reduce weed competition and yield loss. Similarly, in peanut production in India and Ghana, maximum pod yield occurred when weeds were removed within 4 wks after planting [19,20], while Agostinho et al. [21] determined the critical period of weed control in Brazil for five peanut cultivars was from 7 to 65 d after planting. Everman et al. [17] reported that the critical period of interference with mixed broadleaf weed species in peanut was from 2.6 to 8 wks after planting.

Martin et al. [22] stated that weeds could remain in canola (*Brassica napus* L.) up to the four-leaf stage (17–38 d after emergence) even at the 5% yield loss level and even given high levels of weed pressure.

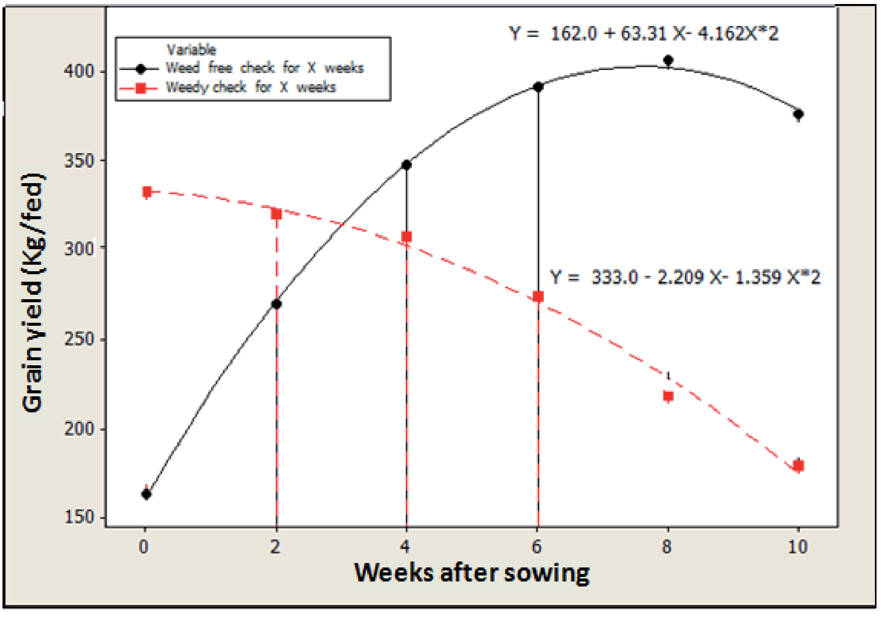

Figure 2. Critical period of weed interference in sesame.

d. Depending on row spacing, the sesame canopy may take as many as 60 d to completely shade the ground. On the other hand, with closer row spacing such as drill-seeded sesames, there is no possibility of being able to use mechanical or manual cultivation to control weeds.

e. Sesame self-defoliates while it is maturing and drying down, thus introducing another period of vulnerability to weeds once the sunlight is again able to reach the soil surface.

f. In manual harvest, the sesame is cut separately from the weeds; therefore, there is little to no weed seed in the harvested grain. In mechanical harvest, weeds are cut at the same time as the sesame. If the weeds are still green, they can introduce moisture into the sample which may lead to heating and ruining of the seed.

g. Many weed seeds have a similar size and/or specific gravity of sesame seeds, making it difficult to separate from the weed seed.

h. It is difficult to evaluate sesame because it has a great ability to compensate for injury, stunting, and stand reduction. In many of the herbicide studies where sesame injury is severe following preemergence (PRE) and postemergence (POST) herbicide treatments, sesame yields are acceptable because the plants can compensate for open space by additional branches with capsules. However, branching can only compensate for gaps of less than 30 cm. Wider gaps not only lead to lower yields, but also let light through the canopy to encourage late-season weed emergence and growth.

The majority of sesame in the world is grown manually – manual planting, manual control of weeds, and manual harvest [23,24]. In countries where there is abundant, cheap manual labor, this methodology will persist. However, in countries such as the USA, the price of sesame will not allow for much manual labor. Planting, cultivating, and harvesting are done mechanically; however, in some cases, manual labor is still required for weed control. The purpose of weed research over the past 23 years conducted by the authors has been to control weeds with the use of herbicides. There have been numerous studies published on preplant [25,26], PRE [27-28], POST [29], postemergence-directed (PDIR) [30], and summaries of various studies [7].

Preplant-incorporated herbicides such as trifluralin, pendimethalin, and ethalfluralin can provide good weed control, but a stand of sesame can be destroyed if precipitation moves the soil particles containing the herbicide into the root zone at an early growth stage [25,26]. Preemergence herbicides such as acetochlor, diuron, linuron, and *S*-metolachlor typically provide favorable control (70–80%) of small seeded grasses and dicots [27,28]. There are numerous studies that have shown that alachlor can be and is used in most of the sesame growing countries around the world [31,32]. The POST graminicides, fluazifop-p-butyl and sethoxydim, provide good grass control at all stages of growth, while clethodim may cause injury when sprayed during the reproductive phase [29]. As for broadleaf weeds, diuron and fluometuron applied POST provide reasonable control but there is risk of injury to sesame [29]. With the exception of glyphosate, which will kill sesame when applied POST, most of these herbicides will moderately to severely damage sesame but will not kill it [7].

In the USA, the use of glyphosate or glufosinate-ammonium tolerant hybrids or varieties in most of the major field crops such as corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean [*Glycine max* (L.) Merr.] is widespread [33-35] and has led to the evolution of many weeds that are now resistant to these herbicides [36-39]. New cotton and soybean transgenic varieties with traits conferring resistance to the synthetic auxin herbicides, 2,4-D and dicamba (2,4-DR and DR, respectively) have been developed [40-42] and are expected to be quickly adopted by growers who will use these traits to control glyphosate- and glufosinate-ammonium-resistant weed species [43-46]. This type of methodology cannot be used for weed control in sesame because, similar to wheat (*Triticum aestivum* L.), the current markets will not accept a genetically modified sesame.

There is a second issue with the universal use of POST herbicides. When the plants reach a certain height or size, the POST herbicides do not reach below the canopy or on the ground in the seed zone. In the past, many US growers used directed sprays in traditional cropping systems, but much of that equipment has been idle for many years. However, because of weed resistance issues in many areas of the country [33-35], there has been a resurgence in the use of this type of equipment that might be utilized in sesame production. The directed spray equipment covers fewer acres per hour compared to the newer over-the-top sprayers and thus has not been the preferred method of weed control; however, growers have begun to use directed sprayers on sesame.

There has been a federal label in the USA for the use glyphosate as a PDIR spray as long as the glyphosate is applied between the rows and not on the main stem of the sesame [47]. Many commercial fields have used this type of application successfully and it has been particularly effective against viney weeds such as morningglory (*Ipomea* spp.) and smellmelon (*Cucumus melo* L) as long as the vines have grown into the furrows. In some cases, the vines of these weeds start climbing the sesame plant from the ground line and are not covered by the glyphosate application. In addition, there are weeds, such as cutleaf groundcherry (*Physalis angulata* L.), that can grow under poor light conditions found below the crop canopy and eventually grow above the sesame. Also, glyphosate does not provide any soil residual control.

In previous work with the PDIR systems, Grichar et al. [30] used some of the more common cotton herbicides and sprayed those to 5 and 15 cm of the sesame main stem. Sesame injury was greatest when herbicides were applied to 15 cm of the main stem compared to herbicide applications made to 5 cm of the main stem height. Glyphosate at 0.84 kg ae/ha and pyrithiobac-sodium at 0.07 kg ai/ha resulted in the greatest sesame stunting (28–90%) when applied to the 15 cm main stem height. When glyphosate was applied to the 5 cm main stem height, sesame injury was 20% or less. Glyphosate applied to the 15 cm stem height and pyrithiobac applied to the 5 and 15 cm stem height consistently reduced sesame yield when compared with the nontreated control. Glufosinate-ammonium and the premix of linuron plus diuron applied up to the 5 cm stem height caused the least sesame stunting and resulted in no reduction in sesame yield when compared with the nontreated control. It was concluded that up to 5 cm coverage was a safer height because (1) it caused less damage and (2) in a field use setting by growers, the 5 cm height realistically meant the height would be 0–10 cm, whereas setting the height at 15 cm meant the height would be 10–20 cm, a height not commonly utilized by producers and thus introduces more herbicide injury risk to the system.

This study is a continuation of the previous PDIR work [30] and the purpose was to use a wider range of herbicides, with an emphasis on those herbicides that control broadleaf weeds, while eliminating those herbicides that caused too much injury. There are good options for POST treatment of grasses to include fluazifop-p-butyl, sethoxydim, and clethodim [7,29]. Recent work has shown effectiveness with quizalofop [7] and haloxyfop (Hongmei, personal communication). As for POST control of broadleaf weeds, diuron is the only known herbicide that will cause minimal damage to the sesame while controlling many broadleaf weeds [7].

2. Materials and methods

2.1. Research sites

Field studies were conducted during the 2008 through 2010 growing seasons near Uvalde in south Texas and near Lorenzo in the Texas High Plains to evaluate sesame response to herbicides applied PDIR. Fields were selected that had low weed populations so any plant response could be attributed to the herbicide treatment and not weed competition. All plots were manually maintained weed-free and herbicide efficacy was not evaluated. Within 2 d of planting, *S*-metolachor at 1.43 kg ai/ha and glyphosate at 0.4 kg ae/ha were applied to control any existing weeds and provide additional PRE weed control on the nonsprayed areas between the rows. The Uvalde trial was furrow-irrigated, while the Lorenzo field was dryland with no rain after planting in 2009 and 2010. Soil type at Uvalde was a Winterhaven silty clay loam (fine-silty, carbonatic, hyperthermic Fluventic Ustochrepts) with less than 1.0% organic matter and pH 7.8. Soil type at Lorenzo was an Amarillo sandy clay loam (fine-loamy, mixed, thermic Aridic Paleustalf) with 0.8% organic matter and pH 7.8.

2.2. Plot design

A randomized complete-block experimental design was used and treatments were replicated 3 times. Treatments consisted of 12 herbicides applied PDIR no more than 5–10 cm up the main stem of the sesame. A nontreated control was included for comparison. Plot size was five rows (76 cm apart) by 9.1 m in south Texas and four rows (101 cm apart) by 7.3 m in the Texas High Plains. Only the two middle rows were sprayed and the other rows were nontreated and served as buffers. Carfentrazone-ethyl, glufosinate-ammonium, pyraflufen-ethyl, propazine, linuron, and linuron plus diuron were used as standards since they had been tested previously [30]; however, carfentrazone-ethyl, glufosinate-ammonium, and pyraflufen-ethyl were eliminated after 2008 since they provide little or no residual activity [48-50] and; therefore, would not be as beneficial as those herbicides that possessed residual activity. Linuron, the combination of linuron plus diuron, and propazine were used as standards in subsequent years. Acetochlor, as an encapsulated formulation, was released for testing and used only in 2010. The encapsulated formulation of acetochlor was labeled in the USA for use in corn, cotton, milo (*Sorghum bicolor* L. Moench), and soybean in 2011 [51].

2.3. Herbicides and spraying information

Herbicides and doses included in the study are shown in Table 1. At Uvalde, herbicides were applied in water using a CO2-pressurized backpack sprayer calibrated to deliver 190 L/ha at 180 kPa. Spray tips were one Teejet® 8004E nozzle (Teejet Spraying Systems Co., P.O. Box 7900, Wheaton, IL 60188) on each side of the row adjusted to spray a PDIR spray band up to 10 cm

http://dx.doi.org/10.5772/61554

in height on sesame stem and 10–15 cm band on the soil to simulate the spray of a PDIR spray applicator. At the Lorenzo location, a tractor-mounted compressed-air Redball® sprayer with Teejet® 8002E spray tips (one on each side of row) calibrated to deliver 93 L/ha at 207 kPa was used in 2008, while in 2009 and 2010 a similar setup to the Uvalde location was used. Herbicides were applied when sesame was 38–76 cm in height. All PDIR herbicide sprays with the exception of glufosinate-ammonium included a crop oil concentrate (AgriDex®, a blend of 83% paraffin-based petroleum oil and 17% surfactant, Helena Chemical Company, Suite 500, 6075 Poplar Avenue, Memphis, TN 38137) at 1.0% v/v.

Common name	**Trade name**	**Manufacturer**	**Dose (kg ai/ha)**
Acetochlor	Warrant	Monsanto Company	1.27
Carfentrazone-ethyl	Aim	FMC	0.02
Diuron	Direx	Makhteshim Agan	1.12
Fluometuron	Cotoran	Makhteshim Agan	1.12
Flumioxazin	Valor	Valent, USA	0.07
Glufosinate-ammonium	Liberty	Bayer Crop Science	0.58
Imazethapyr	Pursuit	BASF	0.07
Prometryn	Caparol	Valent USA	1.12
Propazine	Milo-Pro	Albaugh, Inc	0.84
Pyraflufen-ethyl	ET	Nichino America, Inc	0.002
Linuron	Lorox	DuPont Crop Protect.	1.12
Linuron + diuron	Layby Pro	Tessenderlo Kerley, Inc	0.56 + 0.56

Table 1. Herbicides, trade names, manufacturer, and dose used in study.

2.4. Sesame varieties, planting, and harvesting

Sesame variety “Sesaco 32” was planted at all locations. Planting dates at the Uvalde location were late May in all years, while at the Lorenzo location, sesame was planted late June in 2008, 2009, and early June in 2010. Sesaco 32 was seeded approximately 1.0 cm deep at a seeding rate of 3.4 kg/ha at both locations. When the sesame plants in plots were dry enough to harvest, the sesame plants were hand-harvested, dried, threshed with a plot thresher, cleaned, and weighed.

2.5. Data analysis

An analysis of variance was performed using the ANOVA procedure for SAS [52] to evaluate the significance of herbicides on sesame response and yield. Fishers Protected LSD at the 0.05 level of probability was used for separation of mean differences.

3. Results

Since not all herbicides were included in each year of this study, no attempt was made to combine data over years or locations; therefore, each year is presented separately.

3.1. South Texas (Uvalde)

3.1.1. Sesame stunt

In 2008, when rated early season (21 d after herbicide application), imazethapyr caused the greatest stunting (97%), while carfentrazone-ethyl and linuron alone caused at least 50% sesame stunting (Table 2). Sesame in the linuron plots recovered substantially (17%) by 70 d after herbicide application. Flumioxazin, glufosinate-ammonium, and propazine caused 27–37% sesame stunting, while diuron, prometryn, and the combination of diuron plus linuron resulted in 8% or less stunting (Table 2). When rated later in the growing season (70 d after herbicide application), sesame stunting with carfentrazone-ethyl and imazethapyr was still greater than 60%, while flumioxazin, propazine, pyraflufen-ethyl, and linuron caused 17–48% sesame stunting. Diuron, glufosinate-ammonium, prometryn, and the combination of diuron plus linuron caused 10% or less stunting (Table 2).

In 2009, when rated 26 d after herbicide application, flumioxazin, propazine, and the combination of diuron plus linuron caused significant sesame stunting (>30%), while in 2010, only flumioxazin caused stunting that was greater than the nontreated control (Table 2).

3.1.2. Sesame yield

In 2008, all PDIR herbicide treatments with the exception of diuron, glufosinate-ammonium, and prometryn reduced sesame yield when compared with the nontreated control (Table 2). In 2009, all of the PDIR treatments except acetochlor, fluometuron, and prometryn reduced the sesame yield when compared to the nontreated control. In 2010, only flumioxazin reduced yield when compared with the nontreated check.

		Stunt (%)[b]				Yield		
		2008				(Kg/ha)		
Treatment[a]	Dose (Kg/ha)	Early	Late	2009	2010	2008	2009	2010
Nontreated	-	0	0	0	0	1233	1309	1230
Acetochlor	1.27	-	-	3	0	-	1334	1159
Carfentrazone-ethyl	0.02	63	62	-	-	336	-	-
Diuron	1.12	8	1	8	0	1159	1061	1344
Fluometuron	1.12	-	-	11	2	-	1183	1282

Flumioxazin	0.07	37	48	78	30	717	446	724
Glufosinate-ammonium	0.58	30	10	-	-	1054	-	-
Imazethapyr	0.07	97	65	-	-	583	-	-
Prometryn	1.12	3	4	8	0	1168	1122	1294
Propazine	0.84	27	22	53	5	968	536	1180
Pyraflufen-ethyl	0.002	15	25	-	-	975	-	-
Linuron	1.12	50	17	14	0	986	1033	1234
Diuron + Linuron	0.56 + 0.56	3	3	30	3	901	919	1272
LSD (0.05)		24	15	27	8	213	235	327

[a] All PDIR herbicides, except glufosinate-ammonium, included a crop oil concentrate at 1.0 % v/v.

[b] Stunt ratings taken 21 and 70 d after herbicide application in 2008 and 26 and 13 d after herbicide application in 2009 and in 2010, respectively.

Table 2. Sesame stunt and yield in south Texas as influenced by postemergence-directed herbicide sprays.

3.2. High Plains (Lorenzo)

3.2.1. Sesame stunt

In 2008, all herbicides applied PDIR, with the exception of pyraflufen-ethyl, caused stunting that was greater than the nontreated control (Table 3). Greater than 10% stunting was observed when using flumioxazin or propazine. In 2009, prometryn, diuron, or linuron caused 4–7% sesame stunting when compared with the nontreated control; however, flumioxazin caused severe stunting (43%). Fluometuron and propazine caused stunting (1%) that was not different from the nontreated control. In 2010, all herbicides, with the exception of fluometuron (2%), caused minor stunting (4–5%), while flumioxazin again caused severe stunting (23%).

3.2.2. Sesame yield

Sesame was not harvested in 2009 at Lorenzo due to dry growing conditions during the growing season and yields which were extremely low (<100 kg/ha). Sesame yields were extremely low in 2010 also due to the extreme drought and high temperatures [53]. In neither year (2008 or 2010) was sesame yields reduced from the nontreated control with any herbicide treatment (Table 3). However, in 2010, yields from sesame treated with propazine or the combination of diuron plus linuron resulted in a yield increase over the nontreated control. The lack of yield differences from the nontreated control may be due to the fact that although sesame stunting, with the exception of flumioxazin, was greater than the nontreated control in many instances, injury was less than 10%. Sesame does have the ability to compensate for reduced populations and early season injury due to herbicides [5]. In numerous yield analyses, Langham [8] found little difference in yield from sesame populations of 10–26 plants per meter. Many sesame cultivars can adjust to the population; that is, produce more branches (and therefore more capsules) under low populations. However, branching can only compensate for gaps of about 30 cm. Wider gaps not only lead to lower yields but also let light through the canopy to encourage weed emergence and growth [7].

		Stunt (%)[b]			Yield (Kg/ha)	
Treatment[a]	Dose (Kg/ha)	2008	2009	2010	2008	2010
Nontreated	-	0	0	0	818	302
Acetochlor	1.27	-	-	0	-	330
Carfentrazone-ethyl	0.02	7	-	-	859	-
Diuron	1.12	5	6	4	751	333
Fluometuron	1.12	-	1	2	-	314
Flumioxazin	0.07	12	43	23	650	351
Glufosinate-ammonium	0.58	5	-	-	789	-
Prometryn	1.12	7	7	5	706	313
Propazine	0.84	13	1	4	706	430
Pyraflufen-ethyl	0.002	3	-	-	859	-
Linuron	1.12	5	4	5	664	367
Diuron + Linuron	0.56 + 0.56	5	-	4	661	430
LSD (0.05)		3	4	3	200	87

[a] All PDIR herbicides, except glufosinate, included a crop oil concentrate at 1.0 % v/v.

[b] Stunt ratings taken 28–30 d after herbicide application.

Table 3. Sesame stunt and yield in the High Plains of Texas as influenced by postemergence-directed herbicides sprays.

3.3. Combined data over PDIR studies

3.3.1. Yields

Yield data from Grichar et al. [30] and this study were combined and averages were compiled with the treatment yield average compared to the nontreated control and expressed as a percent increase or decrease from the nontreated (Table 4). As mentioned earlier, yields from Lorenzo in 2009 were not taken due to the extremely dry conditions, while yields at Uvalde were consistent due to the use of furrow irrigation to supplement rainfall. All PDIR herbicide treatments, with the exception of acetochlor, glyphosate plus prometryn, paraquat, and pyraflufen-ethyl, resulted in yield reductions when compared with the nontreated control (Figure 3). In 2010, Monsanto launched an encapsulated formulation of acetochlor (Warrant®) [51]. This encapsulated formulation of acetochlor provides greater crop safety in several crops, including soybean, and was designed to give

PRE control of weeds as well as assist in POST weed control in acetolactate synthase (ALS) and glyphosate-resistant weeds [54,55]. The encapsulated formulation requires limited moisture for activation, helps minimize a negative crop response, and also can extend weed control for up to 40 d [54,55]. Glyphosate, paraquat, and pyraflufen-ethyl all have resulted in sesame injury and yield reductions in several studies [7,29]. Glyphosate is cleared in the USA for use in sesame as a burndown, with wiper applicators, and/or hooded sprayers in row middles [6,7,47]. For burndown use, glyphosate should be applied before, during, or just after planting but before the sesame seedlings emerge [47]. Glyphosate applied POST to sesame will result in plant death or yellowing of the sesame and a lack of capsule formation for 1–3 wks after application. When capsule formation does somewhat recover, the capsules will be smaller and will have less seeds and seed weight [6,7].

4. Discussion

4.1. Ideal herbicide and those that have shown the most promise

The ideal PDIR herbicide is one that will kill existing weeds and also provide residual PRE soil activity. The killing of the weeds with POST herbicides can be broken down into 2 categories: those herbicides that are systemic and kill the whole plant and those herbicides that just kill the plant tissue that comes in contact with the herbicide. In the latter category, if there is enough dead tissue, the weed may die.

There are nine herbicides that are selective to sesame: acetochlor, diuron, fluometuron, glufosinate-ammonium, linuron, linuron plus diuron, paraquat, prometryn, and pyraflufen-ethyl (Table 5). Acetochlor can be eliminated because it has residual control but will not kill existing weeds. Glufosinate-ammonium, paraquat, and pyraflufen-ethyl can be eliminated because they will kill existing weeds but do not have a residual effect.

The following are the most promising for use as a PDIR spray application:

1. Diuron, a systemic urea herbicide that inhibits photosynthesis and has been used to control various weeds in cotton [56], is selective to sesame as a PRE, POST [7], or as a PDIR treatment and is effective against both broadleaf weeds and grasses [57]. In Venezuela, diuron at 0.6 and 1.2 kg/ha reduced sesame yield, but yield would have been much lower without effective weed control [58]. In the USA, in one year, diuron at 0.8 and 1.7 kg/ha resulted in adequate weed control without apparent crop injury, whereas in another year, there was stand reduction and chlorosis [59]. In later work by Grichar et al. [27], they reported that diuron at 1.12 kg/ha reduced sesame stands and caused sesame injury in one year in the Texas High Plains area; however, in south Texas no adverse effects with diuron were seen in the two years.

2. Linuron, a substituted urea herbicide, is selective to sesame as a PRE or PDIR treatment [7] but may severely damage sesame as a POST treatment [7,29,30]. Multiple direct applications of linuron, when the sesame was 15–30 cm tall, did not kill the sesame

	Lorenzo				Uvalde				
	Kg/ha								Deviation[a]
Treatment	2006	2007	2008	2010	2007	2008	2009	2010	%
Nontreated	612	810	818	302	1223	1233	1309	1230	
Acetochlor	-	-	-	330	-	-	1334	1159	1.8
Carfentrazone-ethyl	608	1080	859		996	336			-10.7
Diuron	-	-	751	333	-	1159	1061	1344	-2.7
Flumioxazin	-	-	650	351	-	717	446	724	-30.6
Fluometuron	-	-	-	314	-	-	1183	1282	-0.5
Glufosinate-ammonium	556	1047	789	-	1173	1054	-	-	-0.4
Glyphosate	526	830	-	-	984	-	-	-	-10.4
Glyphosate + diuron	382	760	-	-	917	-	-	-	-22.9
Glyphosate + prometryn	462	964	-	-	1440	-	-	-	4.1
Imazethapyr	-	-	-	-	-	583	-	-	-52.7
Lactofen	494	882	-	-	1191	-	-	-	-4.3
Linuron	-	1046	664	367	1272	986	1033	1234	-0.7
Linuron + diuron	552	567	661	430	1386	901	919	1272	-7.1
Paraquat	630	1014	-	-	1062	-	-	-	5.0
Prometryn	-	-	706	313	-	1168	1122	1294	-4.9
Propazine	-	750	706	430	1317	968	536	1180	-8.6
Pyraflufen-ethyl	588	1068	859	-	1446	975	-	-	6.1
Pyrithiobac	412	298	-	-	345	-	-	-	-55.9
Trifloxysulfuron	588	477	-	-	687	-	-	-	-29.6
Trifloxysulfuron + prometryn	520	690	-	-	1194	-	-	-	-10.7
LSD (0.05)	90	210	200	87	264	213	235	327	

[a] Average deviation from the nontreated.

Table 4. Sesame yields for all trials from 2006 through 2010.

and controlled morningglory and smellmelon (author's personal observation). Linuron is effective against both broadleaf weeds and grasses [60]. Santelmann et al. [61] found slight phytotoxicity and a reduction in sesame yield with linuron at 2.24 kg/ha.

3. Linuron plus diuron (marketed in the USA as Layby Pro) is selective to sesame as a PRE or PDIR treatment but may severely damage sesame as a POST application [7]. Linuron plus diruon is effective against both broadleaf weeds and grasses [62].

4. Prometryn may prevent sesame germination when applied PRE, will severely damage sesame when applied POST [7], and is selective to sesame when applied PDIR. Prometryn is effective against both broadleaf weeds and grasses [63] and has been effective against morningglory (*Ipomoea* spp.) in field studies (author's personal observations). In irrigated studies in Ethiopia, prometryn at 1.0 kg/ha was safely used on sesame and at the 1.9 kg/ha dose resulted in less than 10% sesame injury. In a similar trial under natural rainfall, prometryn at 2.2 kg/ha completely eliminated the crop [64]. In other studies in Ethiopia under irrigated conditions, prometryn applied PRE at 3.2 kg/ha provided excellent weed control with negligible crop damage. However, under rain-fed conditions, prometryn at 0.8 kg/ha caused 100% sesame mortality [65].

5. Fluometuron has produced mixed results when applied PRE [7] and is selective to sesame as a POST [7] or PDIR treatment. Flumeturon provides control of annual grasses and broadleaf weeds [66]. However, fluometuron is not as effective against many weeds as the previously mentioned herbicides (author's personal observations). In India, fluometuron did not perform as well as alachlor or dichlormate [67]. In Bulgaria, fluometuron at 1.0 kg/ha applied 2 d after sowing controlled annual broadleaf weeds [68]. In the USA, fluometuron doses of 0.3 and 1.1 kg/ha had no effect on sesame height or population, provided good weed control, and had comparable yields to the nontreated control in south Texas [25]. Later, Grichar et al. [27] reported that fluometuron at 1.12 kg/ha in the High Plains region of Texas reduced sesame stand and caused injury in one of two years, while no stand reduction or injury was noted at the south Texas location. Fluometuron applied POST may injure cotton and delay maturity [69]. Guthrie and York [69] stated that growers may resort to this type of application when an insufficient height differential between the crop and weeds prohibits PDIR herbicide applications.

4.2. Herbicides that should not be used

The results of these studies clearly show that the following herbicides should not be used PDIR on sesame: flumioxazin, glyphosate plus diuron, imazethapyr, pyrithiobac, and trifloxysulfuron. With 100% potential reduction in sesame yield if weeds overtake a field, herbicides that cause about 10% sesame injury or yield reduction should not be ruled out. These include carfentrazone, glyphosate, and propazine. Although trifloxysulfuron plus prometryn resulted in just over 10% reduction in yield from the nontreated (Table 4), this combination should probably be avoided since a serious reduction in yield resulted from the use of trifloxysulfuron alone (30%).

Glyphosate is an interesting option because at times it appears to not cause much sesame injury and at other times it will kill many sesame plants. In one instance in a field with a very high sesame population, which resulted in dominant and minor plants [5], the glyphosate killed the majority of the minor plants and resulted in high yields. In this situation, the minor plants are similar to weeds in that they utilize moisture and fertility and yet do not contribute a commensurate amount of seed yield. Even though the glyphosate plus prometryn treatment actually increased yield, it is difficult to recommend its use since there is only one trial where

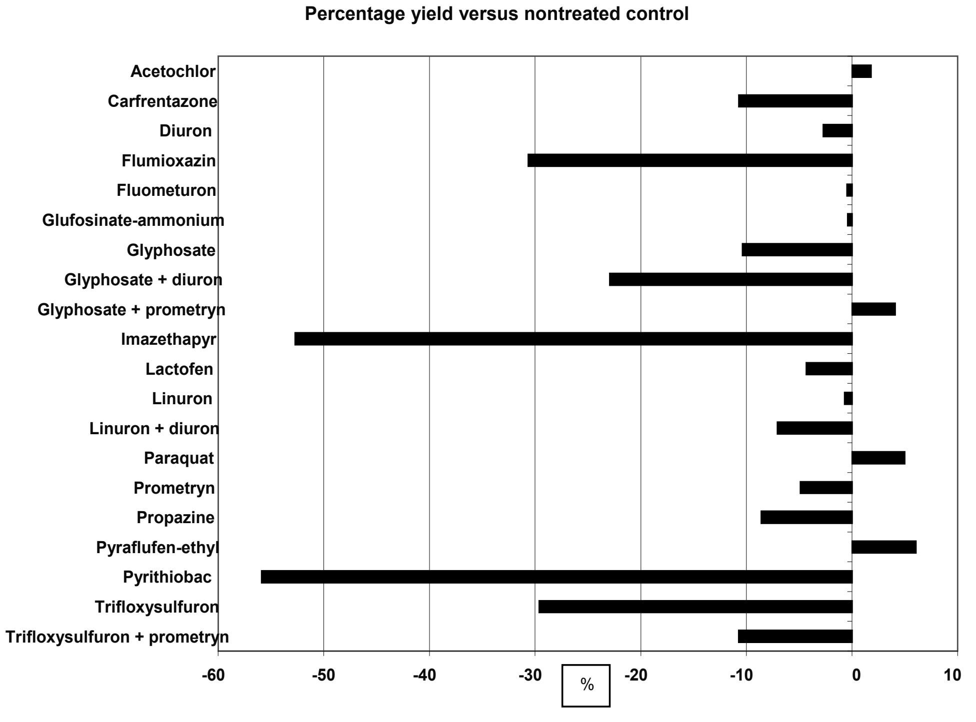

Figure 3. Influence of herbicides applied PDIR to sesame yield.

the results were positive, and glyphosate has been too inconsistent with respect to sesame injury. Carfentrazone and propazine should be considered in a rescue situation when no other herbicides are available.

4.3. Other considerations

As with all herbicides, plant stress may reduce systemic herbicide activity and account for relatively poor herbicide performance. Buhler and Burnside [70] noted that glyphosate was less effective on drought-stressed annual grass species than actively growing plants. Contact herbicides such as carfentrazone-ethyl, diuron, or lactofen are not as dependent on translocation for activity and their activity is not as adversely affected by drought-stressed plants [71,72]. Also the size of the sesame and the weed are important factors [73,74]. One of the weeds that has become more prevalent in the southwestern USA is false ragweed (*Parthenium hysterophorus* L.). Once this weed reaches 30–60 cm in height, spraying the lower 5 cm (as with a PDIR herbicide) will not kill the weed. Similarly, large smellmelon plants are not totally killed with POST herbicides; however, smellmelon growth is slowed and the vines do not climb the sesame plants to sunlight.

Further research is needed on timing of the herbicide application. In all of these trials, the herbicides were applied 4–5 wks after planting when the sesame was in the late juvenile stage and sesame plants were about 38–70 cm tall and only one sesame variety was tested. One of the practical issues in farming is: what is the earliest time that the herbicide can be applied without damaging the sesame? Because all of the studies were done on fields that had been planted in late May or early June, the heights of the plants and the heights of the first capsule were similar. The herbicide spray contacted the sesame stem below the lowest leaf; thus, there was virtually no damage to any of the leaves. The exception was with the use of paraquat where the effects of physical drift could be seen on the lower leaves (author's personal observations).

Treatment	Residual	Contact	Systemic	Mode of action	Sesame[a]
Acetochlor	Yes	No	No	Shoot growth inhibitor	Sel
Carfentrazone-ethyl	No	Yes	No	PPO inhibitor	Stox
Diuron	Yes	Yes	No	Photosynthesis II (P II) inhibitor	Sel
Flumioxazin	Yes	Yes	No	PPO inhibitor	Tox
Fluometuron	Yes	No	No	P II inhibitor	Sel
Glufosinate-ammonium	No	No	Yes	Glutamine synthase inhibitor	Sel
Glyphosate	No	No	Yes	EPSP synthase enzyme inhibitor	Tox
Glyphosate + diuron	Yes	Yes	Yes	EPSP synthase enzyme inhibitor + P II inhibitor	Tox
Glyphosate + prometryn	Yes	Yes	Yes	EPSP synthase enzyme inhibitor + P II inhibitor	Tox
Imazethapyr	Yes	No	Yes	ALS or AHAS synthesis inhibitor	Tox
Lactofen		Yes	No	PPO inhibitor	Ssel
Linuron	Yes	Yes	No	P II inhibitor	Sel
Linuron + diuron	Yes	Yes	No	P II inhibitor	Sel
Paraquat	No	Yes	No	P I inhibitor	Sel
Prometryn	Yes	Yes	No	P II inhibitor	Sel
Propazine	Yes	No	No	P II inhibitor	Stox
Pyraflufen-ethyl	No	Yes	No	PPO inhibitor	Sel
Pyrithiobac	Yes	Yes	No	ALS or AHAS synthesis inhibitor	Tox
Trifloxysulfuron	Yes	No	Yes	ALS or AHAS synthesis inhibitor	Tox
Trifloxysulfuron + prometryn	Yes	Yes	Yes	ALS or AHAS synthesis inhibitor + P II inhibitor	Stox

Abbreviations: Sel, selective to sesame (does not damage sesame); SSel, somewhat selective to sesame (some damage to sesame, sesame recovers); Tox, toxic (substantial reduction of sesame production); STox, somewhat toxic (enough reduction that probably cannot be used).

Table 5. Mode of action of herbicides on weeds and effect on sesame.

When using the number of days after planting as a criterion for applying a herbicide, the ratio of the portion of the stem being struck by the herbicide to the rest of the plant may be significantly different in some situations. The height of the first leaf at 4–5 wks after planting is affected by the following:

- Daylength. Commercial crops planted in late March to early April in the Lower Rio Grande Valley of Texas have much shorter internodes and when 5–10 cm tall, the herbicide spray would come in contact with the leaves. The plants also start flowering earlier and may be in the prereproductive stage instead of the juvenile stage. The longest day of the year is 21 June and crops planted around this time have the longest internodes in areas with high temperatures.
- Temperatures. In years when the air temperatures are low during the early portion of the growing season (such as 2014), the internodes are shorter and the plants are generally more susceptible to stresses in the early weeks.
- Moisture and fertility. High moisture and fertility in the first 2–3 wks will lead to longer internodes and not be a problem. However, in low resource crops, the internodes may be short enough to affect the interaction between the herbicide and the plants.

In waiting for the sesame plants to get tall enough to spray, the weeds also getting taller and will likely be less susceptible to the herbicides [75,76]. Grichar and Dotray [75] reported that lactofen control of Palmer amaranth (*Amaranthus palmeri* S. Wats) was greater when applied to 2–5 cm tall compared with either 15–20 cm or 25–30 cm tall plants. Mayo et al. [76] concluded that Palmer amaranth control generally decreased as application timing was delayed for aciflurofen, imazethapyr, and lactofen.

Also, it has been observed, when diuron and fluometuron were applied in a time of application study, damage to sesame was more severe 2 wks after planting than at any other stage of sesame growth (unpublished data). It is reasonable to expect that a PDIR application at this growth stage would result in more damage. However, research needs to be conducted because it is different to have a PDIR spray contact only the lower leaves versus a POST over the top application where all of the top leaves and the apical meristem are contacted.

Acknowledgements

The authors wish to thank Sesaco Corporation for funding this research. Also, Kevin Brewer, Dwayne Drozd, Lyndell Gilbert, Bill Klesel, Shay Morris, and Terry Weimers for maintenance, plot spraying, and harvesting.

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Chapter 3

Evaluation of Pre- and Postemergence Herbicide Combinations for Broadleaved Weeds in Sugar Beet

Irena Deveikyte, Lina Sarunaite and Vytautas Seibutis

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61437

Abstract

Lithuania sugar beet growers have few herbicide options available for weed management. Six field trials were conducted at the Institute of Agriculture, Lithuania, in order to evaluate the effects of chemical weed management in sugar beet. Treatments included untreated and hand-weeded control and several rates of phenmedipham plus desmedipham plus ethofumesate, phenmedipham, ethofumesate, triflusulfuron, chloridazon, and metamitron. Pre- and postemergence and only postemergence applications similarly affected weed control. Phenmedipham plus desmedipham plus ethofumesate was more effective for controlling weeds when applied in combination with metamitron, triflusulfuron, and chloridazon. The significantly lowest efficacy for weed control was phenmedipham combined with ethofumesate and metamitron as compared to the phenmedipham plus desmedipham plus ethofumesate. Reducing the doses of phenmedipham plusdesmedipham plus ethofumesate from 114+89+140 g a.i. ha^{-1} to 91+71+112 g a.i. ha^{-1} and 68+53+84 g a.i. ha^{-1} in mixture with triflusulfuron resulted in the increase of weed biomass. Full (45 g a.i. ha^{-1}) and reduced doses (30 g a.i. ha^{-1}) of triflusulfuron with phenmedipham plus desmedipham plus ethofumesate similarly affected weeds. The herbicides investigated did not have any negative influence on sugar beet productivity and quality.

Keywords: Weeds, herbicides combination, sugar beet

1. Introduction

Weed competition is one of the major factors which limit sugar beet production in the world [1]. Weed–crop interactions are based on competition for water, nutrients, and light and allelopathic effects may also play a small role. In sugar beet weed interference, all these factors are important too, but light is of prime importance. Weeds may also interfere with harvest operations, making the process less efficient [2]. Due to the fact that a lot of weeds can grow above the sugar beet canopy and reduce the amount of photosynthetic radiation reaching the crop, these weeds are stronger competitors compared to smaller weeds [3, 4]. In a weed free crop stand, photosynthesis in sugar beet is more efficient and nutrient accumulation in the sugar beet root is higher [5]. Left uncontrolled, weeds may reduce yield, interfere with harvest, reduce the value of the crop, and increase future weed problems. The yield of sugar beet roots and sucrose can be severely decreased by weeds, the extent of the decrease being dependent upon competitive ability, weed density, and the length of time that weeds compete with the crop. The total potential losses from weeds would be between 26 and 100% of the potential crop yield [6-8].

Sugar beet is very sensitive to weed competition from the early stages of growth [9, 10]. Sugar beet is not competitive with emerging weeds until it has at least 8 true leaves [7]. Therefore, effective control of weeds at early stages seems to be more important than that at later developed stages [10]. The length of weed-free period affected yield of sugar beet very markedly [11]. When sugar beet and weeds grow together 30 days after emergence of sugar beet, the root yield is decreased up to 45% [12]. As control of weeds is delayed, the yield lost may be decreased by 1.5% for each day the crop is left unweeded, although sugar beet has some ability to recover from an early check [13]. Understanding the emergence characteristics of weeds can be helpful in determining the optimum time to apply postemergence herbicide [11].

Weed control in sugar beet is accomplished with herbicides, mechanical tillage, cultural practices, and hand labor. Control of weeds with herbicides is generally more profitable than allowing weeds to compete with the crop. Herbicides play an important role for weed control in sugar beet production [14, 15]. For high efficacy of chemical method, the timing of application is very important. Weeds have to be small (cotyledon stage) to ensure successful weed control [16]. The doses of herbicides could be reduced by applying at the early growth stage of the weeds, when the first seed leaves start to appear [14, 15]. The application of lower doses leads to reduction of negative impact of herbicides on environment and cuts expenditures for beet production [17].

In recent years, the use of preplant-applied herbicides has declined and use of postemergence herbicides has increased. The most popular active ingredients are phenmedipham, desmedipham, ethofumesate, metamitron, triflusulfuron-methyl, lenacil, clopyralid, and chloridazon [7, 18]. The range of weed species controlled by each herbicide is also limited and so mixtures of herbicides are applied [7, 15, 19, 20]. Sugar beet is applied by tank-mix herbicides combinations several times after crop emergence [15, 21, 22]. Mixtures of postemergence, broad-spectrum herbicides have to be applied to control the wide range of weed species in sugar beet crops [23, 24].

Field experiments were carried out in 2004–2005 and 2010–2012 on arable fields located at the Institute of Agriculture in Central Lithuania. The objective of this study was to evaluate the efficacy of different herbicide mixtures used in recommended and reduced doses on broad-leaved weeds applied pre- and postemergence in sugar beet. Treatments included preemergence application of chloridazon (Pyramin Turbo, 520 g ai l^{-1}) and metamitron (Goltix SC, 700 g ai l^{-1}) and postemergence application of the mixtures of phenmedipham plus desmedipham plus ethofumesate (Betanal Expert, 274 g ai l^{-1}) with chloridazon, metamitron, triflusulfuron-methyl (Caribou, 500 g ai kg^{-1}), ethofumesate (Nortron, 500 g ai l^{-1}), and of the mixtures of phenmedipham (Betasana, 160 g ai l^{-1}) with ethofumesate, metamitron, mineral oil, and of the mixtures of phenmedipham (Kontakt SC, 320 g ai l^{-1}) with ethofumesate, metamitron, rapeseed oil, and of the mixtures of phenmedipham (Betasana) with ethofumesate, metamitron, raps oil. Soil texture was loam consisting of 14.5–17.7% clay, 34.8–39.9% silt, 44.7–51.1% sand. Humus content amounted to 1.6–2.4%, and pH – 6.1–6.9. The field was fertilized with nitrogen, phosphorus, and potassium at the ratio of 105–120:80–120:120–170 kg ha^{-1}. Mineral fertilizers were incorporated into the soil during cultivation. Sugar beet was planted with 45 cm row space, at a density of 15 plants m^{-2}. The herbicides were tank-mixed and applied postemergence at three different dates. The first application was done at the early cotyledon stage of weed growth. Subsequent applications were applied when the next weed flush emerged or 10–17 days after the first flush. The plot size was 2.5 m x 10 m. The herbicides in the experiment were broadcast-applied. The amount of water was 200 l ha^{-1}. Weed dry weight was measured two times: four weeks after herbicide application and before harvest. At the time of assessment a quadrat of 0.20 m x 1.25 m was randomly thrown in each plot. Weed control was assessed by visually estimating the % control relative to the ground cover and vigor of each weed species in the untreated plots. Weed samples were dried at 105°C for 24 h and weighed. Weed density and dry weight data were transformed to $\sqrt{x+1}$. The data were analyzed with ANOVA and LSD test.

2. Weed flora in sugar beet

In much sugar beet growing areas, dicot weeds of the families Chenopodiaceae, Asteraceae, Brassicaceae, and Polygonaceae are of major importance. The monocots are less important compared to dicot weeds [2, 5]. Broadleaf weeds often grow to a height two to three times that of sugar beet by mid-summer. Annual broad-leaved weeds are usually more competitive than annual grasses [25].

The botanical surveys of species were conducted before herbicide application. Overall, 24 weed species were found. The number of weeds found in 2004–2005 and 2010–2012 was from 41 to 108 weeds m^{-2}. In 2011 and 2012, the germination of weeds was lowest in sugar beet; the weed number was 41 and 49 m^{-2}, respectively. Weeds abundantly germinated in 2005, the number of weeds was 108 and 106 m^{-2}, respectively. The dominant weed species in all years were *Chenopodium album* L. (from 11 to 62 weed m^{-2}), *Lamium purpureum* L. (from 3 to 30 weed m^{-2}), *Stellaria media* (L.) Vill. (from 2 to 40 weed m^{-2}), *Viola arvensis* Murray (from 2 to 18 weed m^{-2}), and *Thlaspi arvense* L. (from 1 to 14 weed m^{-2}). In Latvia, the most frequent species of annual dicots in sugar beet were: *Tripleurospermum perforatum* (Merat.) M. Lainz, *Chenopodium album, Fallopia convolvulus* (L.) Löve, *Capsella bursa-pastoris* (L.) Medik, and *Stellaria media* [26]. *Chenopodium album* was the dominant weed species from the 19–24 species indentified. This species accounted for 10–58% of the total weeds documented. Accroding to literature on the population dynamics of a common arable weed, *Chenopodium album*, and its interactions with an arable crop, sugar beet, where *Chenopodium album* and other weeds may also be a considerable problem [7]. Our research data revealed that *Galium aparine* L., *Veronica arvensis* L., and

Erysimum cheiranthoides L. were present at a low frequency (Figure 1). Other weeds such as *Tripleurospermum perforatum Fumaria officinalis* L., *Fallopia convolvulus*, *Lapsana communis* L., *Polygonum aviculare* L., *Polygonum persicaria* L., *Capsella bursa-pastoris*, *Sinapis arvensis* L., *Euphorbia helioscopia* L., *Myosotis arvensis* (L.) Hill, *Chaenorhinum minus* (L.) Lange., *Centaurea cyanus* L., *Silene pratensis* (Rafn) Godr., *Anagalis arvensis* L., *Myosurus minimus* L., and *Galeopsis tetrahit* L. were less common species. These species germinated in only a few years of the study.

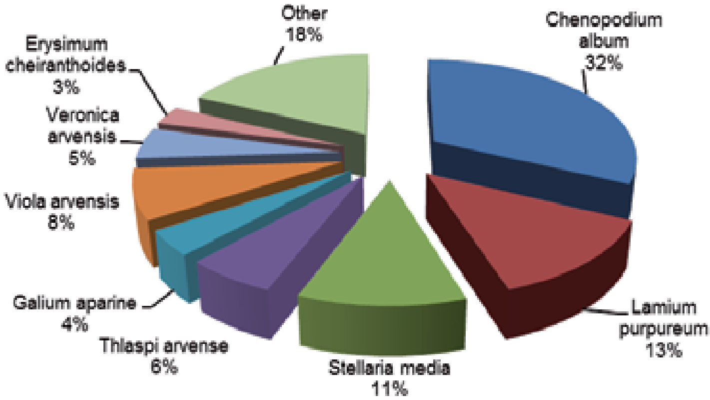

Figure 1. Weed species in sugar beet before herbicide application data averaged over 2004–2012

3. Sensitivity of weeds to phenmedipham, desmedipham, ethofumesate, metamitron, chloridazon, and triflusulfuron combinations at preemergence application

Weed control in crops is mainly based on the use of herbicides because they are efficient and easily applied [27]. Weed control is one of the most difficult agricultural arrangements in sugar beet growing because of low crop interference with weeds [11]. After herbicide use, significant changes in weed flora were noted in terms of abundance and share of some weed species on total weed community [28, 29]. Herbicides for control of dicots can only be used until the crop starts to develop true leaves and their efficacy decreases as the weeds grow [30].

Weed control programs in sugar beet include both pre- and postemergence herbicide treatments [31]. The effectiveness of preemergence residual herbicides decreases with reductions in rainfall or soil moisture content [32]. Preemergence application of soil herbicides is used limitedly because it strongly depends on soil moisture [33]. Therefore, less than 10% of the total sugar beet crop is treated with preemergence herbicides. The remaining 90% depends solely on a selection of postemergence herbicides to maintain season-long weed control [34].

The advantage of soil applied residual herbicides is that they reduce the number of weeds that emerge with the crop and often sensitize survivors to subsequent postemergence sprays. When residual herbicides are used after sowing, they must be applied to the soil surface before sugar beet seedlings emerge or crop damage may result. Preemergence herbicides are important for the subsequent postemergence applications and provide some flexibility with timing and selection of postemergence treatments [35].

The main preemergence residual broad-leaved weed control herbicides used on sugar beet crops are chloridazon and metamitron. Chloridazon is a pyridazinone herbicide with pre-emergence and postemergence activity. This herbicide is usually applied prior to emergence of beet and weeds, and may also be applied postemergence to control common lambsquarters in combination with other herbicides [36]. Metamitron is a 1, 2, 4-triazinone herbicide which is absorbed predominantly by the roots, but also the leaves. This herbicide is applied predrilling incorporated, pre- and postemergence. Metamitron is applied in tank-mix with other herbicides postemergence [37].

Our research data revealed that the efficacy of herbicides varied from 35.0 to 100% (Table 1,2). In 2010, the efficacy of herbicides was higher than in 2011 because the growing season of 2010 started later than normal and the spring. rainfall was higher than the perennial average Total amount of rain was significantly higher and amounted to 20 and 80%, respectively, as compared to long-term average. In April and May of 2011, dry weather prevailed. The amount of precipitation was 42 and 90% of that as the long-term average, respectively. Air temperature, soil moisture, and relative humidity affected herbicide efficacy [38].

Treatment	Efficacy in 1 month after DAA, %				
	CHEAL	POLCO	STEME	LAMPU	EPHHE
Weedy check	0	0	0	0	0
Metamitron, 2100 g a.i. ha^{-1} – predrilling (T_0); Metamitron, 700 g a.i. ha^{-1} – $T_{1,}$T2; Raps oil, 0.5 l ha^{-1} – T0, T1, T3	98.5b	89.0b	100.0a	98.3b	98.8b
Metamitron, 1400 g a.i. ha^{-1} –T_1; Metamitron, 1050 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1} – T_0,T_1, T_3	100.0a	95.3a	99.8a	99.5a	100.0a
Metamitron + phenmedipham + ethofumesate, 1400+160+35 g a.i. ha^{-1} – T_1; Metamitron + phenmedipham + ethofumesate, 1050+160+35 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1} – T_0,T_1, T_3	100.0a	99.8a	100.0a	100.0a	100.0a

Note. The means followed by the same letter within a line are not significantly different according to Fisher's Protected LSD test (P<0.05).

Table 1. Effect of the herbicide combinations on weeds in sugar beet, 2010

The tank mixture of metamitron at 1050 g ai ha^{-1} or 1400 g ai ha^{-1} with phenmedipham at 160 g ai ha^{-1} and ethofumesate at 35 g ai ha^{-1} and raps oil at 0.5 l ha^{-1} sigificantly reduced *Chenopo-*

dium album (CHEAL), *Fallopia convolvulus* (POLCO), *Lamium purpureum* (LAMPU), and *Euphorbia helioscopiai* (EPHHE) as compared with pre- and postemergence application of metamitron (Table 1). The higher efficacy (95.3–100.0%) on weeds was achieved when metamitron at 1050 g ai ha^{-1} or 1400 g ai ha^{-1} with raps oil at 0.5 l ha^{-1} was applied postemergence.

In 2011, in dry years, the efficacy of metamitron alone was lower (35.0–62.5%) than when in combination with other herbicides (Table 2). Preemergence application of metamitron provided significantly lower efficacy on *Chenopodium album*, but significantly higher efficacy on *Galium aparine* (GALAP) than postemergence application of this herbicide. In other studies, metamitron controlled *Chenopodium album* up to two weeks after application thoroughly. One month after application *Chenopodium album* regenerated [38]. The combination of metamitron with phenmedipham plus desmedipham plus ethofumesate plus raps oil resulted excellent control of weeds (>96%).

Treatment	Efficacy in 1 month after DAA, %				
	CHEAL	POLCO	STEME	GALAP	VIOAR
Weedy check	0	0	0	0	0
Metamitron, 2100 g a.i. ha^{-1} – predrilling (T_0); Metamitron, 700 g a.i. ha^{-1} – T_1,T2; Raps oil, 0.5 l ha^{-1}, T0, T1, T3	56.3de	43.8bc	48.8bc	56.3b	37.5b
Metamitron, 1400 g a.i. ha^{-1} –T_1; Metamitron, 1050 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1} – T_0,T_1, T_3	62.5bc	42.5bc	43.8cd	46.3c	35.0b
Metamitron + phenmedipham plus tthofumesate, 1400+160+35 g a.i. ha^{-1} –T_1; Metamitron + phenmedipham + ethofumesate, 1050+160+35 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1}, T_0,T_1, T_3	98.0a	98.5a	100.0a	97.8a	96.8a

Note. The means fallowed by the same letter within a line are not significantly different according to Fisher's Protected LSD test (P<0.05).

Table 2. Effect of the herbicide combinations on weeds in sugar beet, 2011

Herbicides can interact with each other in tank-mixed and can cause damage or reduce crop populations [35]. The visual crop injury symptoms included deformation and yellowing of leaves, growth reduction, and thinning (Figure 2). Statistical analysis of the data on visual injury showed that the effect of year with treatments was significant. The visual injury in metamitron-treated plots ranged from 64% of preemergence and 0% of postemergence when herbicides were applied at low doses (Table 3). Sugar beet recovered from metamitron injury even at high doses [39]. Other studies also have reported no or less injury of sugar beet plants with the application of herbicides at reduced doses compared to full dose application [40]. No visible symptoms of phytotoxicity on sugar beet plants were noticed after postemergence metamitron and this herbicide tank-mixed with phenmedipham plus desmedipham plus ethofumesate plus raps oil application. The phytotoxicity of herbicides decreased with time. To avoid injury, growth depressions, or leaf damage of sugar beet plants, herbicide use has to be carefully adjusted especially to the prevailing weather conditions [41].

Treatment	2010			2011		
	7 DAT	14 DAT	28 DAT	7 DAT	14 DAT	28 DAT
Weedy check	0	0	0	0	0	0
Metamitron, 2100 g a.i. ha^{-1} – predrilling (T_0); Metamitron, 700 g a.i. ha^{-1} – $T_{1,}$T2; Raps oil, 0.5 l ha^{-1}, T0, T1, T3	64.0**	61.3**	61.3**	0	0	0
Metamitron, 1400 g a.i. ha^{-1} –T_1; Metamitron, 1050 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1}, T_0,T_1, T_3	0	0	0	0	0	0
Metamitron + phenmedipham + thofumesate, 1400+160+35 g a.i. ha^{-1} –T_1; Metamitron + phenmedipham + ethofumesate, 1050+160+35 g a.i. ha^{-1} – T_2, T_3; Raps oil, 0.5 l ha^{-1}, T_0,T_1, T_3	0	0	0	0	0	0

Note. **differences are statistically significant as compared to the control at P<0.01. $T_{1,}$ T_2, T_3, and T_4 - first, second, third, and fourth application.

Table 3. Visual injury on sugar beet treated with pre- and postemergence herbicides

A

B

Figure 2. Sugar beet injury from preemergence application of metamitron: (a) yellowing, (b) thining

The infestation of *Chenopodium album* (CHEAL), *Fallopia convolvulus* (POLCO), *Galium aparine* (GALAP), *Stellaria media* (STEME), and *Lapsana communis* (LAPCO) were noted (Table 4). After herbicide application, significant changes were noted in the weed flora. When chloridazon was applied preemergence or postemergence, the herbicidal activity was very high. Preemergence application of chloridazon at 2080 g a.i. ha^{-1} and postemergence application of tank-mixed phenmedipham plus desmedipham plusethofumesate with metamitron resulted in excellent control of *Chenopodium album*, *Fallopia convolvulus*, *Galium aparine,* and *Stellaria media* (99–100%) and provided good control of *Lapsana communis* (91 %).

Treatment	CHEAL	POLCO	GALAP	STEME	LAPCO
Weedy check	259.0b	6.8b	9.9b	6.4b	10.8c
Chloridazon, 2080 g a.i. ha^{-1} – predrilling; Phenmedipham + desmedipham + ethofumesate + metamitron, 91+71+114+700 g a.i. ha^{-1} – T_1, T_2	0.0a	0.01ab	0.0a	0.0a	1.0ab
Phenmedipham + desmedipham + ethofumesate + chloridazon 91+71+112+650 g ha^{-1} a.i. – T_1, T_2, T_3	0.9a	0.0a	0.8ab	0.0a	2.0abc
Phenmedipham + desmedipham + ethofumesate + metamitron, 91+71+112+700 g a.i. ha^{-1} – T_1, T_2, T_3	5.0a	0.1ab	0.4ab	0.0a	0.5a

Note. The means followed by the same letter within a line are not significantly different according to Fisher's Protected LSD test (P<0.05).

Table 4. Biomass of prevailing weeds species (g m^{-2}) in sugar beet 1 month after DAA, data averaged over 2004–2005

Postemergence application of chloridazon with phenmedipham plus desmedipham plus ethofumesate resulted in a similar effect on weeds as with the preemergence application. There was no significant difference when comparing both applications. The combination of cloridazon with phenmedipham plus desmedipham plus ethofumesate and metamitron with phenmedipham plus desmedipham plus ethofumesate provided a similar reduction of weed biomass. At the final assessment (3 month after DAA), weed density and biomass decreased compared with first assessment, respectively 42.3 and 25.7% (Table 5).

Treatment	Density, weed m^{-2}		Weed biomass, g m^{-2}	
	1 month after DAA	3 month after DAA	1 month after DAA	3 month after DAA
Weedy check	96.9	55.9	424.7	315.4
Chloridazon, 2080 g a.i. ha^{-1} – predrilling; Phenmedipham + desmedipham + ethofumesate + metamitron, 91+71+114+700 g a.i. ha^{-1} – T_1, T_2	10.6**	3.2*	6.6**	13.1*
Phenmedipham + ethofumesate + chloridazon 91+71+112+650 g ha^{-1} a.i. – T_1, T_2, T_3	5.1**	1.8**	2.3**	1.5*
Phenmedipham + desmedipham + ethofumesate + metamitron, 91+71+112+700 g a.i. ha^{-1} – T_1, T_2, T_3	13.0**	3.2*	11.3**	5.7*

Note. *differences are statistically significant as compared to the control at $P<0.05$, **-at $P<0.01$. T_1, T_2, T_3, and T_4 – first, second, third, and fourth application.

Table 5. Effect of the herbicide combinations on weed density and biomass in sugar beet; data averaged over 2004–2005

The results showed that combination of herbicides significantly affected weed control. A preemergence application of chloridazon at 2080 g a.i. ha^{-1} and two postemergence applications of phenmedipham plus desmedipham plus ethofumesate with metamitron resulted in a similar effect on weeds as a postemergence application of tank-mix of phenmedipham plus desmedipham plus ethofumesate with metamitron and chloridazon. Chloridazon did not influence effectivity. The addition of chloridazon and metamitron similarly affected efficacy of phenmedipham plus desmedipham plus ethofumesate.

4. Combinations of phenmedipham, desmedipham, ethofumesate, metamitron, chloridazon, and triflusulfuron at postemergence application on weeds and sugar beet

Often sugar beets are treated with postemergence herbicides two or more times [16, 20, 28, 40]. Sometimes, more herbicide applications may be necessary [40]. Herbicides are applied at the cotyledon growth stage at 5–14-day intervals [42-45]. The major herbicides are phenmedipham, desmedipham, ethofumesate, chloridazon, metamitron, clopyralid, lenacil, and triflusulfuron-methyl [7, 46-48]. Individual sugar beet herbicides seldom have a wide enough weed control spectrum or residual activity to control all weeds [49], and tank-mixes of different herbicides are commonly used in order to provide a broad spectrum of weed control [35]. The optimization of herbicide application in the sugar beet protection system can be achieved by using mixtures of appropriate components and their selected doses [30, 49]. Mixing compatible herbicides can have benefits such as consumption reduction, increased weed control, economization of the number of applications, release of fewer chemicals into the ecosystem with using their synergistic effects, decrease in residue of herbicide in soil and crops in low concentrations and reduced occurrence of herbicide resistance in weeds [50]. Weed control is often higher from tank-mixed herbicides than from a single herbicide [20, 38, 41, 47, 50, 51]. The herbicides phenmedipham, desmedipham, and ethofumesate are commonly tank-mixed with metamitron, while chloridazon and triflusulfuron are used for broad-leaved weed control in sugar beet [37, 38, 43, 45, 52].

The tank-mix of phenmedipham plus desmedipham plus ethofumesate at 1029 g ai ha^{-1} controlled *Chenopodium album* better than the combination of this herbicide at 822 g a.i. ha^{-1} with triflusulfuron, but the efficacy was lower on *Tripleurospermum perforatum*. Other studies have shown a good control of *Chenopodium album* with phenmedipham plus desmedipham plus ethofumesate [53]. The effect of herbicide treatments on density and biomass of weeds was not significant (Table 6). The addition of triflusulfuron increased the effectiviness of phenmedipham plus desmedipham plus ethofumesate. Results of root yield showed that the combination of herbicides used had no significant effect on root yield as compared to the control.

At the first assessment 1 month after application (DAA), all combinations of herbicides similarly controlled weed density, except where phenmedipham plus desmedipham plus ethofumesate with metamitron and ethofumesate and triflusulfuron were applied (Table 7). At the final

Treatment	Density, weed m^{-2}		Weed biomass, g m^{-2}		Root yield, t ha^{-1}
	1 month after DAA	3 month after DAA	1 month after DAA	3 month after DAA	
Control (cleaned manually)	7.5	1.1	2.1	2.2	75.8
Phenmedipham + desmedipham + ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	1.3	5.5**	59.0**	70.6**	76.1
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Triflusulfuron, 5 g a.i. ha^{-1} – T_2; 10 g a.i. ha^{-1} – T_3	9.7	4.3**	50.2**	64.1**	75.0

Note. **differences are statistically significant as compared to the control at P<0.01.

T_1, T_2, and T_3 – first, second, and third application.

Table 6. Effect of the herbicide combinations on weeds and sugar beet; data averaged over 2010–2012

assessment, at the 3-month DAA, all treatments resulted in similar effect on weed density. The significantly lowest efficacy on biomass of weeds was the combination of phenmedipham with ethofumesate and metamitron (544+500+700 g a.i. ha^{-1}) and raps oil as compared to the phenmedipham plus desmedipham plus ethofumesate (Control II) and other herbicides treatments. Phenmedipham plus desmedipham plus ethofumesate at 1029 g a.i. ha^{-1} and phenmedipham plus desmedipham plus ethofumesate at 822 g a.i. ha^{-1} with triflusulfuron at 15 g a.i. ha^{-1} decreased weed biomass similarly. The biomass of weeds was significantly lower after application of tank-mixed phenmedipham plus desmedipham plus ethofumesate with metamitron, ethofumesate, and triflusulfuron (319+249+492+10 g a.i. ha^{-1}) as compared to other herbicide combinations. Other studies also have reported that phenmedipham plus desmedipham plus ethofumesate was more effective for controlling weeds by applying in a mixture with metamitron than by applying alone phenmedipham plus desmedipham plus ethofumesate [54, 55]. The combination of herbicides decreased sugar beet root yield as compared to the hand-weeded check (Control I). Similar results were reported elsewhere [34, 49]. Only application of phenmedipham with ethofumesate and metamitron (544+500+700 g a.i. ha^{-1}) and raps oil significantly decreased root yield as compared to control I.

5. Sensitivity of weeds to low rates of phenmedipham, desmedipham, ethofumesate, metamitron, chloridazon, and triflusulfuron

In older systems used for weed control in sugar beets, herbicides were applied at a high, single dose. Herbicides are often applied at rates higher than required for weed control under ideal conditions [44]. A single full-rate of phenmedipham and/or desmedipham controlled weeds better and caused less sugar beet injury than half-rate application [56]. By testing the efficacy

Treatment	Density, weed m^{-2}		Weed biomass, g m^{-2}		Root yield, t ha^{-1}
	1 month after DAA	3 month after DAA	1 month after DAA	3 month after DAA	
Control I (cleaned manually)	1.3	0.9	4.8	2.8	80.6
Control II. Phenmedipham + desmedipham + ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	16.2	6.4	86.7	96.4	76.8
Phenmedipham + desmedipham + ethofumesate + metamitron, 91+71+112+700 g a.i. ha^{-1} – T_1; Phenmedipham + desmedipham + ethofumesate + ethofumesate, 114+89+140+100 g a.i. ha^{-1} – T_2; Phenmedipham + desmedipham + ethofumesate + triflusulfuron, 114+89+140 +10 g a.i. ha^{-1} – T_3 (319+249+492+10 g)	7.4**	3.5	14.9**	17.1**	77.2
Phenmedipham + ethofumesate + metamitron 160+100+700 g a.i ha^{-1} – T_1; Phenmedipham + ethofumesate 224+150 g a.i. ha^{-1} – T_2; Phenmedipham + ethofumesate 160+250 g a.i. ha^{-1} – T_3 (544+500+700 g) Raps oil 0.5 l ha^{-1} – T_1, T_2, T_3	20.4	10.5	148.0*	249.7**	72.3**
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Trilusulfuron 5 g a.i. ha^{-1} - T_2; 10 g a.i. ha^{-1} – T_3 (15 g)	14.2	6.0	75.2	94.0	75.9

Note. *differences are statistically significant as compared to the control at $P<0.05$, **-at $P<0.01$.

T_1, T_2, and T_3 – first, second, and third application.

Table 7. Effect of the herbicide combinations on weed density and biomass in sugar beet; data averaged over 2011–2012

of a herbicide over a wide range of rates, growers will have better information to determine the appropriate weed management program that maximizes net returns and minimizes loading of herbicides into the environment [57]. Reducing the recommended dose of herbicides is one of the important instruments in weed management systems. Reduced herbicide applications could be achieved either by reducing the dosages or the number of treatments [53]. The exploitation of competitiveness factors might favor the development of reduced herbicide use strategies for sugar beet [9]. Numerous research studies have indicated a few reasons for the potential successful use of reduced dose: 1) registered doses are set to ensure adequate control over a wide spectrum of weed species, weed densities, growth stages, and environmental conditions; 2) maximum weed control is not always necessary for optimal crop yields; and 3) combining reduced doses of herbicides with other management practices, such as tillage or competitive crops, can markedly increase the odds of successful weed control [30, 58]. Another researcher has shown that it is possible to reduce herbicide doses in sugar beet [38, 44, 45, 50, 59, 60]. For example, Goleblowska and Domaradzki [48] reported that a 50% and 67% dose of Betanal Progress + Goltix + Safari and Betanal Progress + Venzar + Safari consistently produced 94–97% weed control. The half dose of herbicides reduced weed biomass significantly [38]. The lower and frequent doses of herbicide reached comparable or better results in comparison with the traditional system of application [34].

The weed spectrum was similar in both years. The results showed that the efficacy of phenmedipham plus desmedipham plus ethofumesate (1029 g a.i. ha^{-1}) was lower on *Chenopodium album* (CHEAL), *Tripleurospermum perforatum* (MATIN), *Polygonum aviculare* (POLCO), *Thlaspi arvense* (THLAR), and *Viola arvensis* (VIOAR) (Table 8). The additions of metamitron (1050 g) and triflusulfuron (15 g) increased efficacy of phenmedipham plus desmedipham plus ethofumesate. Similar cases of metamitron effectivenes have been reported by many authors [59, 61].

Treatment	CHEAL	MATIN	POLAV	THLAR	VIOAR
Control II. Phenmedipham + desmedipham + ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	33.4b	4.4b	6.3b	1.5b	0.2b
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Trilusulfuron, 5 g a.i. ha^{-1} - T_2; 10 g a.i. ha^{-1} – T_3 (15 g)	12.2ab	1.7ab	2.0ab	0.3ab	0.2ab
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Metamitron 350 g ha^{-1} a.i. – T_1, T_2, T_3 (1050 g)	18.2ab	1.4ab	0.4ab	0.3ab	0.02ab

Note. The means followed by the same letter within a line are not significantly different according to Fisher's Protected LSD test ($P<0.05$).

Table 8. Biomass of prevailing weed species (g m^{-2}) in sugar beet 1 month after DAA; data averaged over 2010–2011

All herbicide treatments had similar effects on weed density, except treatments where combination of phenmedipham plus desmedipham plus ethofumesate (822 g a.i. ha^{-1}) with triflusulfuron were applied (Table 9). The least biomass of weeds was recorded for phenmedipham plus desmedipham plus ethofumesate (1029 g ha^{-1} – full dose). Reducing the doses of phenmedipham plus desmedipham plus ethofumesate by 20% with triflusulfuron and by 40% with metamitron, their efectiviness significantly reduced at final assessment. Metamitron with tank-mixes of phenmedipham plus desmedipham plus ethofumesate had similar effect on weeds compared to triflusulfuron with phenmedipham plus desmedipham plus ethofumesate. Effect of combination herbicides was not significant on sugar beet root yield as compared with control I.

The postemergence trials showed that commercial mixture of phenmedipham plus desmedipham plus ethofumesate (1029 g ha^{-1} – full dose) effectively decreased the biomass of

Treatment	Density, weed m^{-2}		Weed biomass, g m^{-2}		Root yield, t ha^{-1}
	1 month after DAA	3 month after DAA	1 month after DAA	3 month after DAA	
Control I (cleaned manually)	1.8	1.4	2.5	2.5	83.0
Control II. Phenmedipham + desmedipham + ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	11.1	5.5	46.8	44.4	82.4
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Trilusulfuron, 5 g a.i. ha^{-1} – T_2; 10 g a.i. ha^{-1} – T_3 (15 g)	7.2	2.2*	21.2	14.0*	81.1
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Metamitron 350 g ha^{-1} a.i. – T_1, T_2, T_3 (1050 g)	8.2	3.5	18.7	14.2*	81.7

Note. *differences are statistically significant as compared to the control at P<0.05.

T_1, T_2, and T_3 – first, second, and third application.

Table 9. Effect of the herbicide combinations on weeds and sugar beet; data averaged over 2010–2011

Chenopodium album (CHEAL), *Veronica arvensis* (VERAR), and *Galium aparine* (GALAP), but the differences were not statistically significant. In the treatment where by reducing dose of phenmedipham plus desmedipham plus ethofumesate by 40% with triflusulfuron at 30 and 45 g ha^{-1} was applied, the biomass of *Veronica arvensis* (VERAR) was recorded to be higher as compared to that of full dose of phenmedipham plus desmedipham plus ethofumesate. The herbicide combination did not have significant influence on weight of botanical composition of weed flora.

All herbicide combinations similarly affected weed density, except phenmedipham plus desmedipham plus ethofumesate (615 g a.i. ha^{-1}) with triflusulfuron at 30 g a.i. ha^{-1} (Table 11). In this mixture, dose of phenmedipham plus desmedipham plus ethofumesate were the lowest. When the dose of phenmedipham plus desmedipham plus ethofumesate in a herbicide mixture was reduced by 40% and addition of triflusulfuron at reducing dose by 33% (30 g a.i. ha^{-1}) was used, the effectiveness of phenmedipham plus desmedipham plus ethofumesate was not reduced. At the first assessment (1 month after DAA), different herbicide treatments had no significant effect on biomass of weeds. At the final assessment, triflusulfuron with tank-mixes of phenmedipham plus desmedipham plus ethofumesate had a greater effect on biomass of weeds than phenmedipham plus desmedipham plus ethofumesate. When the dose of phenmedipham plus desmedipham plus ethofumesate in this herbicide combination was reduced by 40% the biomass of weeds significantly decreased as compared to phenmedipham plus desmedipham plus ethofumesate of reducing dose by 20%. Weed control from herbicide combinations of phenmedipham plus desmedipham plus ethofumesate with full dose (45 g

Treatment	CHEAL	MATIN	VERAR	POLCO	GALAP
Phenmedipham + desmedipham plus ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	0.00a	0.93ab	0.00ab	2.27b	0.00ab
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Trilusulfuron, 10 g a.i. ha^{-1} – T_2; 20 g a.i. ha^{-1} – T_3 (30 g)	0.00a	0.05ab	0.00ab	0.00ab	0.10ab
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Trilusulfuron, 15 g a.i. ha^{-1} – T_2, T_3 (30 g)	0.25c	1.91b	0.66ab	0.00ab	0.07ab
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Trilusulfuron, 10 g a.i. ha^{-1} – T_1; 15 g a.i. ha^{-1} – T_2; 20 g a.i. ha^{-1} – T_3 (45 g)	0.01abc	0.00ab	0.77b	0.00ab	0.10b

Note. The means followed by the same letter within a line are not significantly different according to Fisher's Protected LSD test (P<0.05).

Table 10. Biomass of prevailing weeds species (g m^{-2}) in sugar beet 1 month after DAA; data averaged over 2011–2012

a.i. ha^{-1}) of triflusulfuron was the highest. Sugar beet yield was not significantly different between herbicide treatments. All herbicide treatments produced lower sugar beet yields than the hand-weeded check. Similar results were reported elsewhere [49, 62].

Treatment	Density, weed m^{-2}		Weed biomass, g m^{-2}		Root yield, t ha^{-1}
	1 month after DAA	3 month after DAA	1 month after DAA	3 month after DAA	
Control. Phenmedipham + desmedipham + ethofumesate, 114+89+140 g a.i. ha^{-1} – T_1, T_2, T_3 (1029 g)	1.5	3.8	3.6	19.1	74.6
Phenmedipham + desmedipham + ethofumesate, 91+71+112 g a.i. ha^{-1} – T_1, T_2, T_3 (822 g); Trilusulfuron, 10 g a.i. ha^{-1} – T_2; 20 g a.i. ha^{-1} – T_3 (30 g)	0.5	1.0	0.2	4.4	70.2
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Trilusulfuron, 15 g a.i. ha^{-1} – T_2, T_3 (30 g)	6.8*	2.0	3.1	4.2*	70.8
Phenmedipham + desmedipham + ethofumesate, 68+53+84 g a.i. ha^{-1} – T_1, T_2, T_3 (615 g); Trilusulfuron, 10 g a.i. ha^{-1} – T_1; 15 g a.i. ha^{-1} – T_2; 20 g a.i. ha^{-1} - T_3 (45g)	3.2	1.0	1.2	1.2*	69.0

Note. *differences are statistically significant as compared to the control at *P*<0.05.

T_1, T_2 and T_3 – first, second, and third application.

Table 11. Effect of the herbicide combinations on weeds and sugar beet; data averaged over 2011–2012

http://dx.doi.org/10.5772/61437

6. Conclusion

All herbicide combinations acted similarly on reduction of the following weed species: *Chenopodium album, Thlaspi arvense, Tripleurospermum perforatum, Polygonum aviculare, Veronica arvensis, Stellaria media,* and *Lapsana communis.* Postemergence application of chloridazon with phenmedipham plus desmedipham plus ethofumesate resulted in a similar effect on weeds compared to preemergence applications. The efficacy of phenmedipham plus desmedipham plus ethofumesate was similar in action as compared to that applied in tank-mixes with chloridazon, metamitron, and triflusulfuron. There were no significant differences on weight of weeds. The addition of chloridazon, metamitron, and triflusulfuron controlled weeds similarly. The significantly lowest efficacy on weeds resulted from a combination of phenmedipham with ethofumesate and metamitron as compared to the phenmedipham plus desmedipham plus ethofumesate. Two reduced doses (by 20% and 40%) of phenmedipham plus desmedipham plus ethofumesate in tank-mix had a significant effect on weeds compared to that of all doses of phenmedipham plus desmedipham plus ethofumesate. Full and reduced doses (by 33%) of triflusulfuron with phenmedipham plus desmedipham plus ethofumesate similarly affected weeds. The herbicides investigated did not have any negative influence on sugar beet productivity and quality.

Acknowledgements

This study has been supported by the UAB "Nordic Sugar Kedainiai."

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Chapter 4

Evaluation of Non-fumigant Pesticides as Methyl Bromide Alternatives for Managing Weeds in Vegetables

Timothy Grey and Theodore Webster

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61635

Abstract

The phase out of methyl bromide (MBr) challenged vegetable growers' abilities to control weeds in low-density polyethylene (LDPE) mulch production systems. The herbicides halosulfuron, fomesafen, *S*-metolachlor, and clomazone are needed as part of the pesticide program in LDPE vegetable production to control weeds including *Cyperus* species. Experiments were conducted during the spring and autumn of 2012, evaluating *Cyperus rotundus*, bell pepper, and cucumber response to these herbicides applied to soil immediately prior to LDPE laying. Halosulfuron, fomesafen, *S*-metolachlor, and clomazone applied to soil under LDPE mulch did not negatively impact stand and growth of bell pepper in spring or autumn experiments, or cucumber in spring trials. However, there was significantly less growth in the autumn experiment as halosulfuron, *S*-metolachlor plus clomazone plus halosulfuron or fomesafen, reduced vine length. *Cyperus rotundus* suppression and control was achieved with halosulfuron alone and when used in combinations with *S*-metolachlor plus clomazone, and combinations of *S*-metolachlor plus clomazone plus fomesafen. These herbicides provided weed control that were comparable to MBr plus chloropicrin (MBrR-C). Using herbicides for control and suppression of *Cyperus rotundus* in combination with safety for pepper and cucumber will allow growers to implement new control strategies into their vegetable production systems.

Keywords: Crop tolerance, clomazone, fomesafen, halosulfuron, *S*-metolachlor

1. Introduction

Effective weed control in fresh market production of vegetable crops is challenging due to the elimination of the preplant soil fumigant methyl bromide (MBr). Purple (*Cyperus rotundus*) and yellow nutsedge (*C. esculentus*) are the most common and troublesome weeds in fresh market vegetable production throughout the southeastern US [1]. The sharp tips of the emerging purple nutsedge shoots readily pierce low-density polyethylene (LDPE) mulch and lead to an exclusive nutsedge infestation (Figure 1), proliferating rapidly as vegetables are supplemented with water and nutrients via drip irrigation from tubes inserted at the time LDPE mulch is laid. Purple and yellow nutsedge are perennial with erect growth and triangular stems. Newly developing nutsedge rhizomes are indeterminate stems sheathed in scaled leaves surrounding pointed meristems [2]. Nutsedge rhizomes, in the absence of light, remain in a heterotrophic growth phase that allows the stem internodes to continue to elongate [3]. The continued lengthening of the rhizomes is responsible for forcing nutsedge leaves through the plastic and into the light, where photomorphogenic cues that lead to leaf formation and expansion are triggered [3]. The use of black polyethylene mulch may alter the environmental characteristics of the cropping system to the benefit of nutsedge species. Research by Webster [4] demonstrated that black LDPE mulch promoted the growth of purple nutsedge plants, relative to a mulch-free check. Under black-opaque LDPE mulch, a single purple nutsedge tuber multiplied to 3,440 shoots covering an area of 22.1 m^2 in 60 weeks. Herbicides that could be incorporated into vegetable systems using LDPE mulch must be effective on *Cyperus* and other weed species. Halosulfuron, fomesafen, clomazone, and *S*-metolachlor provide residual activity toward weed species with control often extending for many weeks or months after applications [5]. In this region, with MBr no longer a weed control option, herbicides are now used to maintain fresh market vegetable production.

2. Importance

The use of LDPE mulch with fumigation to manage weeds, plant pathogens, and nematodes is standard for production of vegetables in the southeastern US [6–10]. Most LDPE mulch is laid for spring vegetable production followed by a second crop in the autumn and potentially a third crop the following spring [7]. Spring vegetables grown after LDPE mulch fumigation include watermelon [*Citrullus lanatus* (Thunb.) Matsum and Nak.], bell pepper (*Capsicum annuum* L.), tomato (*Lycopersicon esculentum* Mill.), squash (*Cucurbita pepo* L.), and eggplant (*Solanum melongena* L.). A second autumn crop often includes cabbage (*Brassica oleracea* L.), eggplant, cucumber (*Cucumis sativus* L.), or squash. This second crop is often transplanted directly into the existing LDPE mulch-covered beds [7, 10] in order to grow two crops in 1 year, minimizing expenses associated with polyethylene mulch and drip tape irrigation by spreading costs over multiple crops. Weed control is critical as bell peppers may be more sensitive to nutsedge interference than other vegetable crops. Gilreath et al. [11] reported that nutsedge densities of approximately 5.4 plant m^{-2} occurring during crop fruit set reduced bell pepper yield by 31%. Motis et al. [12] noted that severe nutsedge infestations of greater than 30 plants m^{-2} could reduce bell pepper yields from 54% to 74%. Therefore, season-long weed control is essential. Residual herbicides will be an integral part of continued fresh market vegetable production. By applying residual herbicides to the soil surface at the time LDPE mulch is laid, weed control could be improved, while also maintaining and extending productive use of the LDPE mulch for subsequent crops.

Figure 1. Purple nutsedge (*Cyperus rotundus*) piercing low-density polyethylene mulch (photo by Sidney Cromer).

3. Background information on LDPE mulch weed control

Methyl bromide was first used as a soil fumigant in France in the 1930s and was tested for nematode control beginning in the 1940s [13], and then used to sterilize soil in the 1950s [14]. It became the standard for broad-spectrum pest control in fresh market vegetable production through the 1990s [15–18]. Herbicides with soil persistence were first used for preemergence (PRE) weed control in agronomic crops beginning in the 1940s [19]. However, there was no need to incorporate herbicides into LDPE mulch fresh market vegetable production, as MBr was effective and consistent in control of multiple pests including most weed species. With the increasing awareness of MBr as an ozone-depleting compound, efforts to decrease its use began in earnest in the early 1990s. Data from the US Environmental Protection Agency (EPA) fact sheets, sales, and usage information indicated the rapid decline in MBr use in the US from greater than 28,000,000 kg in 1991 to less than 2.2% of that baseline level in 2013 (Figure 2), due to restrictive use goals set at the Montreal Protocol in 1991 [7]. In the interim, MBr was often combined with chloropicrin as a means to reduce MBr usage [11]. The goal is to be at less than 0.01% of the 1991 baseline MBr use by 2017 in the US [20]. With the loss of MBr for weed control, herbicide alternatives were immediately considered, as there were several registrations already in place for bare soil production methods. For example, halosulfuron was registered for use in tomato in multiple US states in April 2004 as a pre- and postemergence application. Halosulfuron is now registered for use as a soil preemergence application prior to LDPE mulch laying [21]. While herbicide options are available in LDPE mulch scenarios, crop tolerance and weed control are often a concern and require additional research. There are several herbicides that should be considered as alternatives to MBr in LDPE mulch systems, but the critical factors for their success involve their effectiveness in controlling nutsedges and the level of crop tolerance.

3.1. Halosulfuron

Halosulfuron is a sulfonylurea herbicide that inhibits branched-chain amino acid synthesis [5] with good to excellent control of nutsedges [22, 23]. When soil applied in vegetables, halosulfuron was applied to soil for vegetable growth, its adsorption to soil colloids was highly correlated with soil organic carbon content and inversely related to soil pH. Halosulfuron degradation increases with temperature and lower soil pH, with soil moisture content and soil type further affecting soil persistence. Soil dissipation is primarily by chemical hydrolysis and microbial degradation [5]. Halosulfuron half-life (DT_{50}) ranges from 6 to 98 days, depending on soil moisture and temperature regimes [8, 24] and exhibit hysteresis [25]. Injury from halosulfuron carryover to rotational crops has occurred as a result of its variable soil behavior [26]. This variability in the literature suggests that further evaluation of halosulfuron for weed control using LDPE is needed.

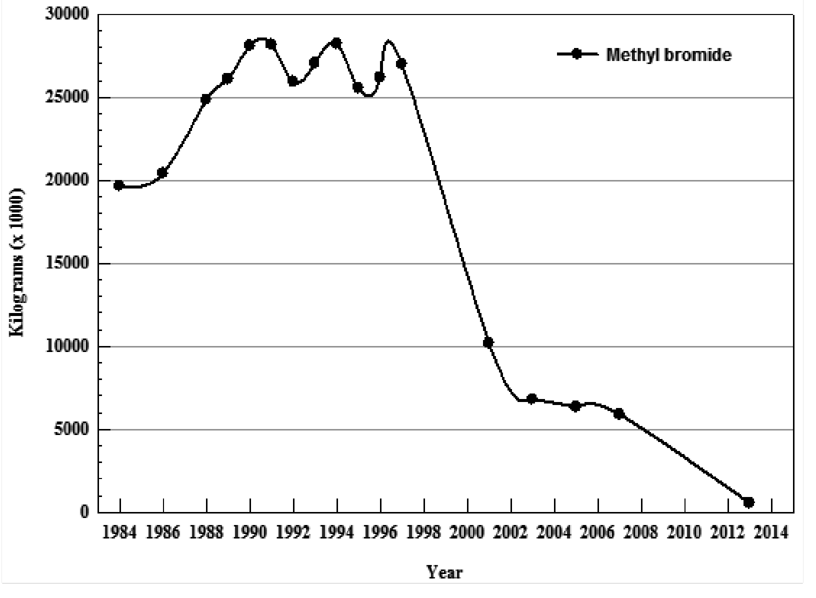


Figure 2. Methyl bromide use in the US (Environmental Protection Agency 2015). The phase out of methyl bromide. Available at http://www.epa.gov/ozone/mbr/index.html).

3.2. Fomesafen

Fomesafen, a member of the diphenyl ether herbicide family, is registered for postemergence application for control of dicot species in agronomic crops. However, it does have soil residual activity [27–29] with a half-life ranging from 6 to 12 months under aerobic conditions [30]. In contrast, fomesafen degradation under anaerobic conditions was less than 3 weeks [5]. Rauch et al. [31] reported fomesafen field DT_{50} varied between 28 and 66 days. Fomesafen has been the focus of several research studies to determine its potential preemergence soil residual activity in vegetables, with testing in tomato for control of American black nightshade (*Solanum* *americanum* Miller) [32], cucurbits for *Amaranthus* spp. and other weeds [33], and crop tolerance in cantaloupe [34] and pepper [35, 36]. When used in combination with other herbicides in tomato production, fomesafen applied to soil prior to laying virtually impermeable film (VIF) mulch provided improved purple nutsedge control compared to fomesafen alone [37]. Fomesafen has exhibited soil activity for yellow nutsedge control [38]. While fomesafen has been evaluated in multiple vegetable crops, the literature suggests that further evaluation of fomesafen for bell pepper and cucumber when applied to soil when using LDPE is needed.

3.3. *S*-metolachlor

Metolachlor is a chloroacetamide herbicide, and its dissipation from soil has been extensively investigated [39–44]. Weber et al. [44] reported that metolachlor sorption, mobility, and soil retention were related to organic matter, clay content, and surface area. As soil organic matter concentration increases, adsorption of metolachlor increases. Metolachlor mobility was inversely related to soil organic matter and clay content. Other studies came to similar conclusions, indicating that metolachlor binding was by physical forces between metolachlor molecules and soil constituent surfaces [44]. Half-life of metolachlor varies with soil temperature, moisture, and organic matter content [5, 45]. *S*-metolachlor is registered for use in pumpkin (*Cucurbita pepo* L.) (POST), bell pepper (PRE), and tomato (PRE) for LDPE mulch production [21]. However, combinations with other herbicides have not been evaluated.

3.4. Clomazone

Clomazone inhibits photosynthesis and carotenoid biosynthesis in higher plants, and application to sensitive species results in bleaching or whitening of photosynthetic tissues, chlorosis, and death [46]. Clomazone is microencapsulated (ME) due to volatility issues [47]. As a soil-applied herbicide, clomazone is currently registered for use in certain US states for cabbage, cantaloupe, cucumber, squash, and watermelon (*Citrullus lanatus* L.) [21]. Field studies have indicated that clomazone provides full-season preemergence weed control in selected cucurbits [48, 49]. As clomazone inhibits carotenoid biosynthesis, chlorosis or "bleaching" of sensitive plants, such as squash, is predicted. Bleaching of squash increased with increasing rates when clomazone was applied either preplant incorporated (PPI) or PRE in bare soil situations [50]. Incorporation of clomazone PPI into the root zone enhances uptake and increases bleaching [50]. Therefore, application sensitivity must be considered when using with LDPE mulch for peppers and cucumbers, but this has not been evaluated.

4. Research

Cucumber and bell pepper production are now more reliant on herbicide combinations applied at the time of LDPE mulch laying when MBr alternative fumigants are either not available or not considered due to worker safety issues. Herbicides must provide residual weed control with minimal potential for vegetable crop injury. Weed control for comparing residual herbicides in vegetables has been performed for multiple crops and scenarios [7, 10, 37]. However, when applied to the soil surface prior to laying, LDPE mulch has not been fully researched. Therefore, this chapter will emphasize herbicide combinations for nutsedge control and response in bell pepper (Table 1) and cucumber (Table 2). Methyl bromide plus chloropicrin (MBR-C) was included as a standard along with a nontreated control.

Herbicide	**Rate**[a]	**2011 test**		**Timing**[c]	
	kg a.i. ha^{-1}			Spring	Autumn
Clomazone ME[b] + fomesafen	0.42 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + fomesafen	0.80 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + fomesafen + clomazone ME	0.80 + 0.28 + 0.42	Spring	Autumn	1 wk PRE	1 wk PRE
Methyl bromide + chloropicrin (50:50)	196 + 196	Spring	Autumn	3 wk PRE	3 wk PRE

[a]Abbreviations: a.i., active ingredient; ME, microencapsulated; PRE, preemergence.
[b]Broadcast rate applied to the soil surface to 91-cm-wide bed as LDPE mulch was laid.
[c]Timing prior to transplanting into LDPE mulch-covered soil.

Table 1. Herbicide, rates, and timing of applications for evaluating purple nutsedge control and bell pepper growth response when applied to soil prior to laying of low-density polyethylene (LDPE) mulch in Georgia.

Herbicide	**Rate**[a]	**2011 test**		**Timing**[c]	
	kg a.i. ha^{-1}			Spring	Autumn
Halosulfuron	0.04	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + clomazone ME + halosulfuron	0.80 + 0.42 + 0.04	Spring	Autumn	1 wk PRE	1 wk PRE
S-metolachlor + clomazone ME + fomesafen	0.80 + 0.42 + 0.28	Spring	Autumn	1 wk PRE	1 wk PRE
Methyl bromide + chloropicrin (50:50)	196 + 196	Spring	Autumn	3 wk PRE	3 wk PRE

[a]Abbreviations: a.i., active ingredient; ME, microencapsulated; PRE, preemergence.
[b]Broadcast rate applied to the soil surface to 91-cm-wide bed as LDPE mulch was laid.
[c]Timing prior to transplanting into LDPE mulch-covered soil.

Table 2. Herbicide, rates, and timing of applications for evaluating purple nutsedge control and cucumber vine growth response when applied to soil prior to lying of low-density polyethylene (LDPE) mulch in Georgia.

4.1. Field studies

Field studies conducted to evaluate herbicide replacement of MBr-C had two distinct research objectives. However, all experiments were conducted similarly. Herbicide application, bed formation, and laying of 32-μm-thick (1.25 mil) LDPE mulch occurred simultaneously. All studies were conducted on Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with 86–88% sand, 8% silt, 4–6% clay, 0.5–1.3% organic matter, and pH ranging from 6.3 to 6.9. Experiments were conducted in the spring and autumn of 2011. The soil was moldboard-plowed 25–30 cm deep, then disk-harrowed. Single beds (0.82 m wide, 22.9 m long, and 20 cm high) were established with a bed shaper. All herbicide treatments were applied as laying of LDPE mulch occurred (Tables 1 and 2). Herbicides were applied with a CO_2-pressurized sprayer calibrated to deliver 187 L/ha at 210 kPa to the bed as it was being prepared. This was in combination with the immediate cover with the LDPE mulch. A single drip irrigation tube with emitters spaced 30 cm apart with a flow rate of 30 ml/min was placed in the center of the bed under the LDPE mulch for application of water and fertilizer. Two separate tests were conducted with bell pepper (Table 1) and cucumber (Table 2). All tests had experimental designs of a randomized complete block with 5 or 12 replications. Treated plots included two rows of bell pepper or cucumber, with in-row spacing based on University of Georgia recommendations for vegetables. Commercial cucumber and bell pepper cultivars commonly grown in the southeastern US during the spring and autumn were selected. Transplanted cucumber "Thunder" and bell pepper "Camelot" were used. Cucumber and bell pepper were then established in the field by hand transplanting (7.5 cm deep into soil). The final comparisons for stand were based on the nontreated control. Irrigation was applied as needed through drip tape, and fertilizer was applied similarly based on University of Georgia recommendations for vegetables. Insects and plant diseases were monitored and sprayed when necessary.

Temperature data used for growing-degree-day (GDD) calculation were collected off-site at the Georgia Weather Monitoring Network, located within 5 km of the experiment [51]. Growing degree days were calculated by using daily minimum and maximum air temperature. Previous studies used a base temperature of 10.4°C for purple nutsedge [52, 62]. Growing degree days provide a more biologically meaningful measure of crop growth compared with time after planting [53, 63].

Crop stand counts, height, and vine length measures were evaluated multiple times after transplanting. Purple nutsedge stand counts were made multiple times during the season on the entire length of the bed. Data were not combined for analysis due to differences in the time of year when the experiments were conducted. Plant height, vine lengths, and vegetable and purple nutsedge stand counts were subjected to analysis of variance (ANOVA) in SAS 9.2 (SAS Institute, 2012). Linear regression models, using the equation,

$$y = b + mx \tag{1}$$

were assessed to determine associations between herbicide treatment and all dependent variables using the REG Procedure in SAS 9.2 with respect to growing degree days. Treatment means are presented for clarity. Mean separation of 95% asymptotic confidence intervals for comparison of parameter estimates was then used to compare each treatment to MBr-C.

5. Purple nutsedge and crop response

Bell pepper, cucumber, and purple nutsedge were measured periodically over time. In spring 2011, greater than 500 GDD were accumulated, over the 2 months the experiment was conducted. In autumn 2011, greater than 550 GDD were accumulated for the 2 months the experiment was conducted.

5.1. Bell pepper

There were no significant differences in crop population density (stand) (data not shown) or plant height response in bell pepper for treatment combinations containing clomazone, fomesafen, or *S*-metolachlor and the nontreated control relative to MBr-C (Tables 3 and 4, Figures 3 and 4). The rate of bell pepper growth (*b*) was less in spring, ranging from 0.056 to 0.062, compared to autumn at 0.071–0.074 cm GDD^{-1}. The *y*-intercepts were also similar for all treatments. These data indicate that bell pepper was very tolerant of these combinations of herbicides, offering an alternative to fumigants, such as chloropicrin, where use is constrained by various buffer zones [52, 62]. Bell pepper has previously shown tolerance to fomesafen in bare soil production [35], but the combination of fomesafen plus *S*-metolachlor with LDPE mulch had variable effects on height and fresh market yield [36]. Fomesafen, *S*-metolachlor, and clomazone are all registered for use with LDPE mulch in Georgia [21].

5.2. Purple nutsedge control in bell pepper

Populations of purple nutsedge varied between the two experiments ranging from 0 to 40 plant m^{-2} at 0–530 GDD after trial initiation (Tables 5 and 6, Figures 5 and 6). This level of purple nutsedge population density has been shown to cause reductions in bell pepper shoot dry weight and fresh market yield [53, 63]. Control of purple nutsedge by combinations of *S*-metolachlor plus fomesafen plus clomazone was similar to MBr-C for the 2011 autumn test (Figure 6). While it was significantly different in the spring from MBr-C, this same herbicide trio provided greater purple nutsedge control than any other tandem combination of clomazone plus fomesafen or *S*-metolachlor plus fomesafen in both experiments (Figures 5 and 6). This supports Florida research where fomesafen plus *S*-metolachlor provided greater control than either herbicide alone [36, 37]. The herbicide trio of *S*-metolachlor plus fomesafen plus clomazone has not been previously described for weed control in vegetables using LDPE mulch. Further research to validate the potential of this trio of herbicides in benefiting bell pepper growers is needed.

5.3. Cucumber

Relative to MBr-C, there were no significant differences in cucumber stand among halosulfuron alone, or combinations containing clomazone, fomesafen, *S*-metolachlor, halosulfuron, and the nontreated control (data not shown). There were no differences among any treatment in the spring experiment for cucumber vine growth rate (*b*), ranging from 0.073 to 0.104 cm GDD^{-1} (Table 7, Figure 7). In contrast, there was variability in the rate of cucumber vine growth in the autumn experiment as all three herbicide treatments had significantly less growth as compared to MBr-C (Table 8, Figure 8). Previous research indicated that cucumber exhibited biomass variability with respect to injury in response to halosulfuron PRE applied in a greenhouse experiment [54]. Halosulfuron is registered for use in cucumber grown with LDPE mulch in Georgia, but injury can occur if proper precautions are not followed during use [21].

S-metolachlor plus clomazone plus halosulfuron, or fomesafen, all had response curves similar to halosulfuron alone (Table 8, Figure 8). Metolachlor has caused reduction in cucumber seedling biomass [55, 56], and is not recommended for use in LDPE mulch systems now due to injury issues. Therefore, these trios of herbicides (*S*-metolachlor plus clomazone plus either fomesafen or halosulfuron) will be too injurious to use with cucumber.

5.4. Purple nutsedge control in cucumber

Similar to the bell pepper experiments, the populations of purple nutsedge varied between the two cucumber tests, ranging from 0 to 32 plant m^{-2} at 0–600 GDD after trial initiation (Tables 9 and 10, Figures 9 and 10). Variability of purple nutsedge control was observed with halosulfuron alone, and the trios of herbicides applied in combination with each other. For the spring experiment (Table 9, Figure 9), all herbicide treatments were different from MBr-C with the rate of purple nutsedge growth of 0.009–0.016 shoots per m^2 GDD^{-1}. In comparison, the rate of purple nutsedge growth for the nontreated control was 0.017 shoots per m^2 GDD^{-1}. For the autumn experiment, halosulfuron provided control similar to MBr-C with *b* values of 0.022 versus 0.018 shoots per m^2 GDD^{-1}, respectively (Table 10, Figure 10). Halosulfuron is registered for use in cucumber [21] and is an effective herbicide that controls purple nutsedge and also reduces the number of new tubers produced [23]. However, variability in nutsedge control has been noted in multiple vegetable crops in bare soil [57–59] and soil under LDPE mulches [37, 60, 61]. Control of purple nutsedge by the trio herbicides combinations was not effective in either experiment (Tables 9 and 10, Figures 9 and 10). These data indicate the variability that can often occur when using herbicides in LDPE mulch systems.

6. Discussion

The complexity and difficulty of managing nutsedge species in vegetable crops have increased with the elimination of methyl bromide. Successful management of nutsedge will require diligent control programs utilizing LDPE mulches along with residual herbicides prior to crop planting, during the cropping season, and between crops (spring and autumn), in order to extend the use of LDPE mulches and reduce costs. This research indicated that combining multiple herbicides could provide control of purple nutsedge in bell pepper and cucumber LDPE mulch production. But variability in purple nutsedge control was observed, which indicates the need for further development as growers incorporate this strategy. Spring and autumn soil-applied residual herbicide treatments prior to LDPE mulch lying did not reduce bell pepper growth. Bell pepper was tolerant of herbicide combinations not previously considered as options for nutsedge control. However, cucumber injury to *S*-metolachlor was unacceptable. Other registered herbicide options should be considered when cucumber is to be grown. Future research should be conducted with the currently evaluated herbicides for other solanaceous and cucurbit crops. Purple nutsedge control was attainable with herbicide applications, but variability was an issue in this research. This should be considered as an area for future research efforts in vegetable production using LDPE mulches.

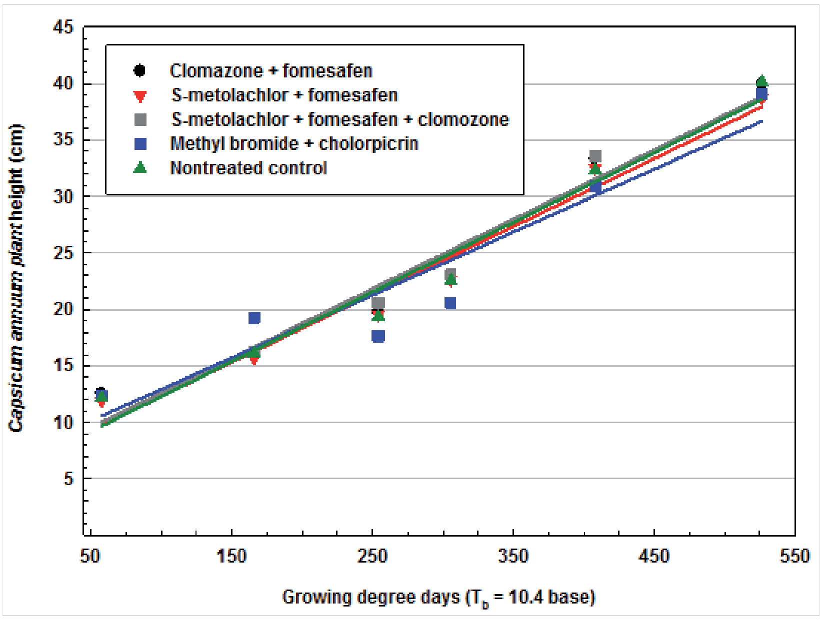
	Rate of bell pepper growth[b]					
Treatment	***y0***[c]		**SE**	***b***		**SE**
Clomazone + fomesafen	6.13	NS[a]	±1.24	0.062	NS	±0.0038
S-metolachlor + fomesafen	7.35	NS	±1.83	0.056	NS	±0.0057
S-metolachlor + fomesafen + clomazone	6.48	NS	±0.67	0.062	NS	±0.0021
Methyl bromide + chloropicrin	6.30	NS	±0.63	0.060	NS	±0.0019
Nontreated	6.48	NS	±0.67	0.062	NS	±0.0021

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for general linear model (GLM) was used for mean separation with 95% asymptotic confidence interval (CI) in SAS 9.2.

[b]Rates of bell pepper growth (*b*)were calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, bell pepper rate of growth; NS, not significant.

Table 3. Rate of bell pepper growth (*b*) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD).



Spring

Figure 3. Pepper height growth response as affected by herbicide treatment when applied to soil surface as low-density polyethylene mulch was laid in spring 2011. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Clomazone + fomesafen; $y = 6.13 + 0.062x$; $R^2 = 0.88$; $P = 0.975$ *S*-metolachlor + fomesafen; $y = 7.35 + 0.056x$; $R^2 = 0.73$; $P < 0.0001$ *S*-metolachlor + fomesafen + clomazone; $y = 6.48 + 0.062x$; $R^2 = 0.93$; $P = 0.0635$ Methyl bromide; $y = 6.30 + 0.060x$; $R^2 = 0.93$; ; $P = 0.527$ Nontreated; $y = 6.48 + 0.062x$; $R^2 = 0.93$; ; $P = 0.0635$

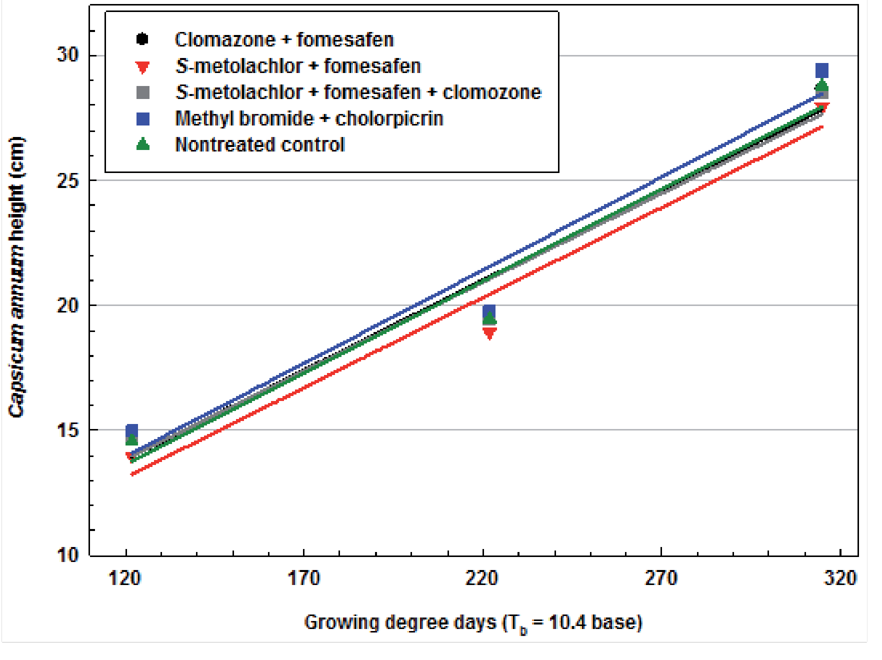
	Rate of bell pepper growth[b]					
Treatment	*y0*[c]		SE	*b*		SE
Clomazone + fomesafen	4.82	NS[a]	±3.68	0.073	NS	±0.0158
S-metolachlor + fomesafen	5.04	NS	±1.64	0.074	NS	±0.0070
S-metolachlor + fomesafen + clomazone	5.35	NS	±1.33	0.071	NS	±0.0057
Methyl bromide + chloropicrin	4.48	NS	±1.50	0.072	NS	±0.0064
Nontreated	5.20	NS	±1.65	0.072	NS	±0.0071

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rates of bell pepper growth (*b*) were calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, bell pepper rate of growth; NS, not significant.

Table 4. Rate of bell pepper growth (*b*) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD).



Autumn

Figure 4. Pepper height growth response as affected by herbicide treatment when applied to soil surface as the low-density polyethylene mulch was laid in autumn 2011. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Clomazone + fomesafen; $y = 4.82 + 0.073x$; $R^2 = 0.55$; $P = 0.147$ *S*-metolachlor + fomesafen; $y = 5.04 + 0.074x$; $R^2 = 0.87$; $P = 0.619$ *S*-metolachlor + fomesafen + clomazone; $y = 5.35 + 0.071x$; $R^2 = 0.81$; $P = 0.0073$ Methyl bromide; $y = 4.48 + 0.072x$; $R^2 = 0.78$; $P = 0.846$ Nontreated; $y = 5.20 + 0.072x$; $R^2 = 0.75$; $P = 0.233$

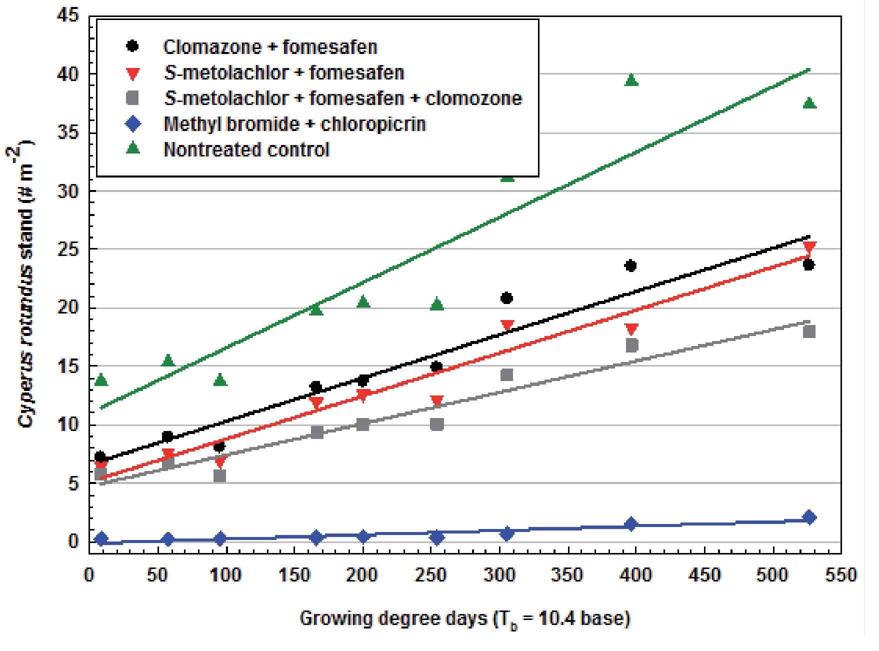
	Purple nutsedge population[b]					
Treatment	*y0*[c]		SE	*b*		SE
Clomazone + fomesafen	6.61	*b*[a]	±1.33	0.037	*b*	±0.0049
S-metolachlor + fomesafen	5.73	*b*	±1.43	0.032	*b*	±0.0062
S-metolachlor + fomesafen + clomazone	3.89	*b*	±1.28	0.033	*b*	±0.0042
Methyl bromide + chloropicrin	0.0	*a*	±1.88	0.004	*a*	±0.0069
Nontreated	11.0	*b*	±1.88	0.056	*b*	±0.0069

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of purple nutsedge growth (*b*) was calculated by linear regression of the herbicide treatments with respect to time, GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, purple nutsedge rate of growth.

Table 5. Purple nutsedge population (*b*) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD) in bell pepper.



Spring

Figure 5. Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011 with bell pepper as a crop. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Clomazone + fomesafen; $y = 6.61 + 0.037x$; $R^2 = 0.38$; $P < 0.0001$ *S*-metolachlor + fomesafen; ; $y = 5.73 + 0.032x$; $R^2 = 0.28$; $P < 0.0001$ *S*-metolachlor + fomesafen + clomazone; $y = 3.89 + 0.033x$; $R^2 = 0.26$; $P < 0.0001$ Methyl bromide; $y = 0.00 + 0.004x$; $R^2 = 0.22$; $P = 0.0002$ Non-treated; $y = 11.0 + 0.056x$; $R^2 = 0.40$; $P < 0.0001$

http://dx.doi.org/10.5772/61635

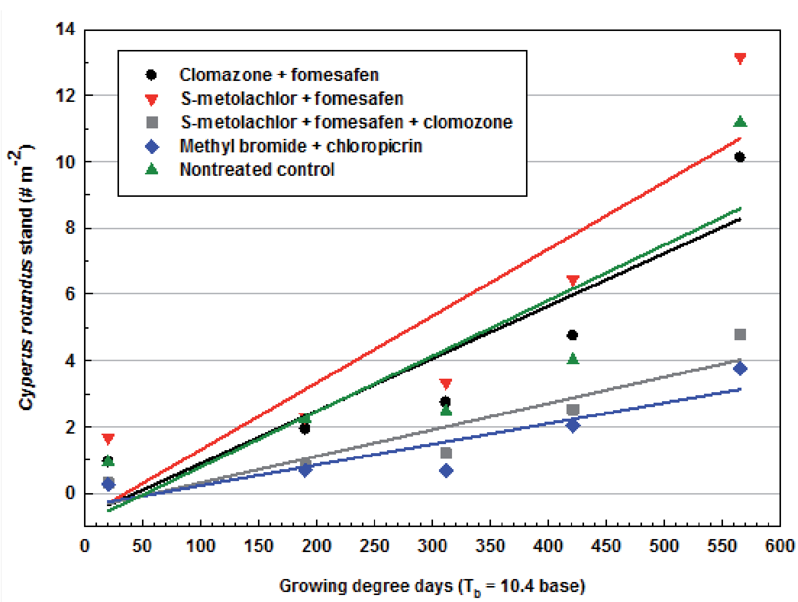
	Purple nutsedge population[b]					
Treatment	***y0***[c]		**SE**	***b***		**SE**
Clomazone + fomesafen	¯0.68	*b*[a]	±1.13	0.016	*b*	±0.0032
S-metolachlor + fomesafen	¯0.71	*b*	±1.83	0.020	*b*	±0.0002
S-metolachlor + fomesafen + clomazone	¯0.48	*a*	±0.63	0.008	*a*	±0.0018
Methyl bromide + chloropicrin	¯0.39	*a*	±0.89	0.006	*a*	±0.0025
Nontreated	¯0.88	*b*	±2.48	0.017	*b*	±0.0070

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of purple nutsedge growth (*b*) was calculated by linear regression of the herbicide treatments with respect to time, GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, purple nutsedge rate of growth.

Table 6. Purple nutsedge population (*b*) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in bell pepper.



Autumn

Figure 6. Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011 with bell pepper as a crop. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Clomazone + fomesafen; $y = -0.68 + 0.016x$; $R^2 = 0.29$; $P < 0.0001$ *S*-metolachlor + fomesafen; $y = -0.71 + 0.020x$; $R^2 = 0.20$; $P = 0.0002$ *S*-metolachlor + fomesafen + clomazone; $y = -0.48 + 0.008x$; $R^2 = 0.24$; $P < 0.0001$ Methyl bromide; $y = -0.39 + 0.006x$; $R^2 = 0.15$; $P = 0.0195$ Nontreated; $y = -0.88 + 0.017x$; $R^2 = 0.14$; $P = 0.0232$

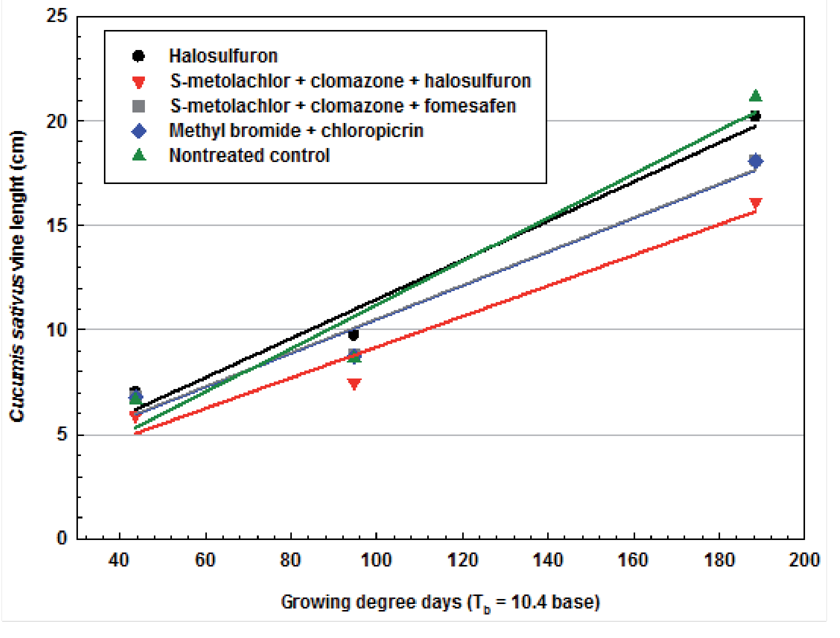
	Rate of cucumber vine growth[b]					
Treatment	$y0$[c]		SE	b		SE
Halosulfuron	2.12	NS[a]	±0.88	0.094	NS	±0.0071
S-metolachlor + clomazone + halosulfuron	1.85	NS	±0.85	0.073	NS	±0.0068
S-metolachlor + clomazone + fomesafen	2.44	NS	±0.83	0.081	NS	±0.0067
Methyl bromide + chloropicrin	2.40	NS	±1.05	0.081	NS	±0.0084
Nontreated	0.79	NS	±1.91	0.104	NS	±0.015

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of cucumber vine growth (b) was calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: $y0$, y-intercept; SE, standard error; b, cucumber vine rate of growth; NS, not significant.

Table 7. Rate of cucumber vine growth (b) as a response to herbicide used in combination with low-density polyethylene mulch in spring 2011 as compared to time in growing degree days (GDD).



Spring

Figure 7. Cucumber vine length growth response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Halosulfuron; $y = 2.12 + 0.094x$; $R^2 = 0.83$; $P = 0.116$ *S*-metolachlor + clomazone + halosulfuron; $y = 1.85 + 0.073x$; $R^2 = 0.77$; $P = 0.0004$ *S*-metolachlor + clomazone + fomesafen; $y = 2.44 + 0.081x$; $R^2 = 0.80$; $P = 0.831$ Methyl bromide; $y = 2.40 + 0.081x$; $R^2 = 0.84$; $P = 0.720$ Non-treated; $y = 0.79 + 0.104x$; $R^2 = 0.72$; $P = 0.013$

http://dx.doi.org/10.5772/61635

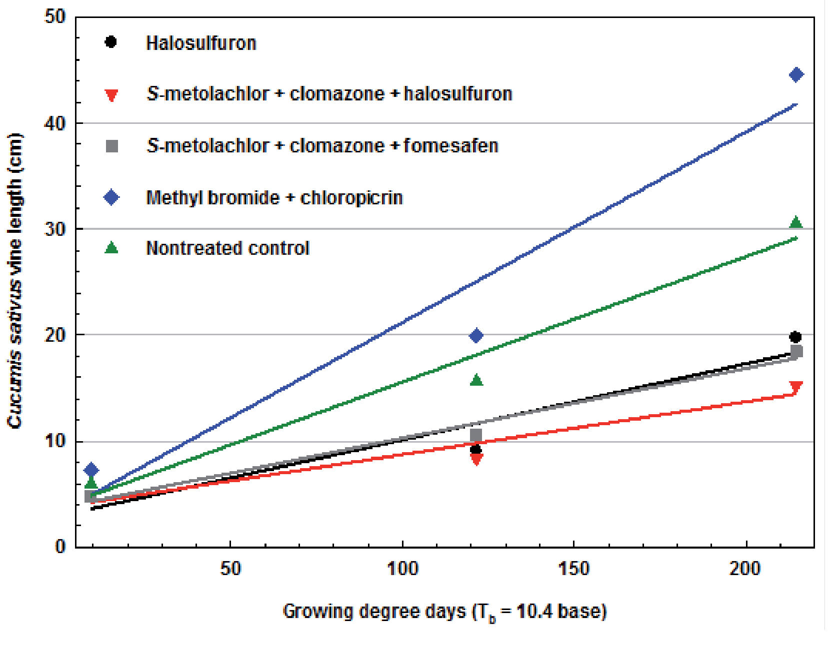
			Rate of cucumber vine growth[b]			
Treatment	***y0***[c]		**SE**	***b***		**SE**
Halosulfuron	2.49	NS[a]	±0.88	0.072	*b*	±0.0062
S-metolachlor + clomazone + halosulfuron	3.77	NS	±0.97	0.050	*b*	±0.0068
S-metolachlor + clomazone + fomesafen	3.70	NS	±1.09	0.066	*b*	±0.0076
Methyl bromide + chloropicrin	3.24	NS	±5.01	0.180	*a*	±0.0352
Nontreated	3.76	NS	±2.32	0.118	*b*	±0.016

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of cucumber vine growth (*b*) was calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, cucumber vine rate of growth; NS, not significant.

Table 8. Rate of cucumber vine growth (*b*) as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD).



Autumn

Figure 8. Cucumber vine length growth response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Halosulfuron; $y = 2.49 + 0.072x$; $R^2 = 0.79$; $P = 0.216$ *S*-metolachlor + clomazone + halosulfuron; $y = 3.77 + 0.050x$; $R^2 = 0.60$; $P < 0.0001$ *S*-metolachlor + clomazone + fomesafen; $y = 3.70 + 0.066x$; $R^2 = 0.68$; $P < 0.0001$ Methyl bromide; $y = 3.24 + 0.104x$; $R^2 = 0.60$; $P = 0.557$ Nontreated; $y = 3.76 + 0.118x$; $R^2 = 0.75$; $P < 0.0001$

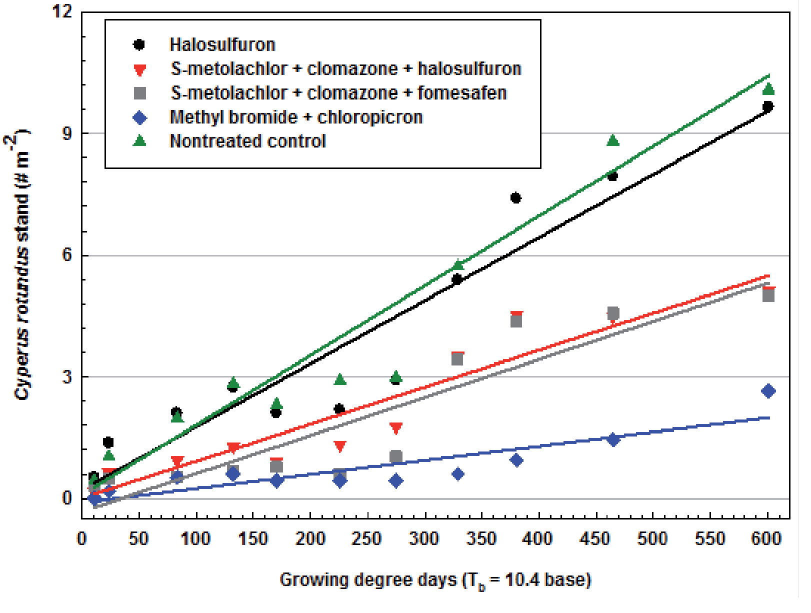
			Rate of purple nutsedge growth[b]			
Treatment	***y0***[c]		**SE**	***b***		**SE**
Halosulfuron	0.21	*b*[a]	±0.55	0.016	*b*	±0.0018
S-metolachlor + clomazone + halosulfuron	0.00	*b*	±0.55	0.009	*b*	±0.0018
S-metolachlor + clomazone + fomesafen	⁻0.33	*b*	±0.55	0.009	*b*	±0.0018
Methyl bromide + chloropicrin	⁻0.11	*a*	±0.77	0.004	*a*	±0.0026
Nontreated	0.09	*b*	±0.77	0.017	*b*	±0.0026

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of purple nutsedge growth (*b*) calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, purple nutsedge rate of growth.

Table 9. Purple nutsedge population (*b*) growth as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in cucumber.



Spring

Figure 9. Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in spring 2011 with cucumber as a crop. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Halosulfuron; $y = 0.21 + 0.016x$; $R^2 = 0.16$; $P < 0.0001$ *S*-metotachlor + clomazone + halosulfuron; $y = 0.00 + 0.009x$; $R^2 = 0.41$; $P < 0.0001$ *S*-merolachlor + clomazone + fomesafen; $y = -0.33 + 0.009x$; $R^2 = 0.47$; $P < 0.0001$ Methyl bromide; $y = -0.11 + 0.004x$; $R^2 = 0.10$; $P < 0.0001$ Nontreated; $y = 0.09 + 0.017x$; $R^2 = 0.46$; $P = 0.0305$

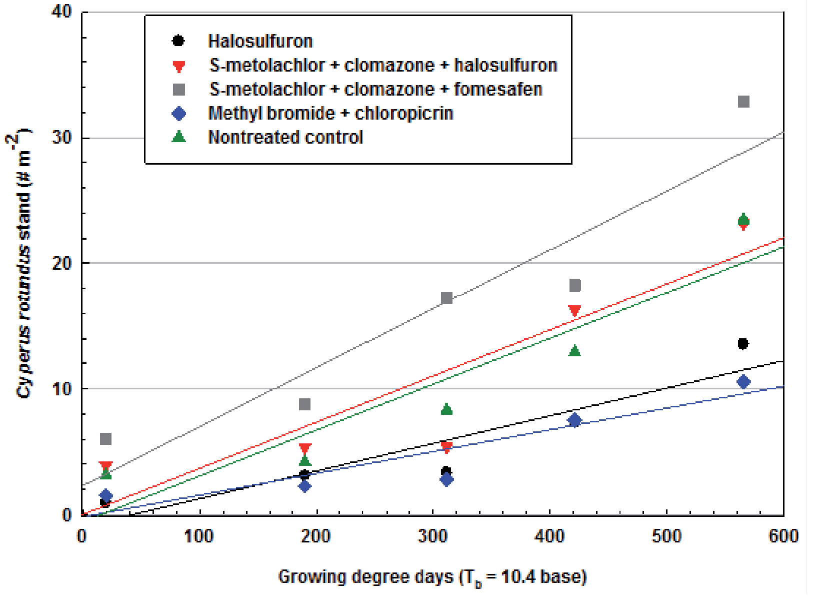
	Rate of purple nutsedge growth[b]					
Treatment	*y0*[c]		SE	*b*		SE
Halosulfuron	¯0.92	*a*[a]	±3.27	0.022	*a*	±0.0091
S-metolachlor + clomazone + halosulfuron	0.0015	*b*	±3.27	0.037	*b*	±0.0091
S-metolachlor + clomazone + fomesafen	2.94	*b*	±3.66	0.034	*b*	±0.0101
Methyl bromide + chloropicrin	¯0.23	*a*	±3.25	0.018	*a*	±0.0092
Nontreated	¯0.57	*b*	±3.27	0.037	*b*	±0.0091

[a]For each herbicide for parameter estimate in each column followed by the same letter are not significantly different ($P \leq 0.05$) as compared to methyl bromide plus chloropicrin. The REG procedure for GLM was used for mean separation with 95% asymptotic CI in SAS 9.2.

[b]Rate of purple nutsedge growth (*b*) calculated by linear regression of the herbicide treatments with respect to time in GDD.

[c]Abbreviations: *y*0, *y*-intercept; SE, standard error; *b*, purple nutsedge rate of growth.

Table 10. Purple nutsedge population (*b*) growth as a response to herbicide used in combination with low-density polyethylene mulch in autumn 2011 as compared to time in growing degree days (GDD) in cucumber.



Autumn

Figure 10. Purple nutsedge stand response as affected by herbicide treatment when applied to soil as the low-density polyethylene mulch was being laid in autumn 2011 with cucumber as a crop. The line represents the linear regression equation with adjusted R^2. Data points are the means of replications: Halosulfuron; $y = -0.92 + 0.022x$; $R^2 = 0.43$; P = 0.0002 S-metolachlor + clomazone + halosulfuron; $y = 0.015 + 0.037x$; $R^2 = 0.23$; P = 0.0084 S-metolachlor + clomazone + fomesafen; $y = 2.94 + 0.034x$; $R^2 = 0.22$; P = 0.0224 Methyl bromide; $y = -0.23 + 0.018x$; $R^2 = 0.38$; P = 0.0006 Nontreated; $y = -0.57 + 0.037x$; $R^2 = 0.42$; P = 0.0003

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Chapter 5

Peanut Performance and Weed Management in a High-residue Cover Crop System

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61650

Abstract

Previous research has indicated that conservation tillage is a viable option for successful peanut production; however, interactions between cover crop residues and peanut growth are not fully understood. Additional information is needed about the effects of varying levels of cover crop biomass on peanut growth and development. Level of cover crop residue may also affect the preemergence herbicide activity through interception and efficacy of weed suppression. The objectives of this peanut research were to determine if varying amounts of cover crop biomass would affect peanut growth, herbicide interception, or weed control. This research also aimed to determine if cover crop management practices (rolling or standing cover) would affect herbicide interception rates. The study consisted of a rye (*Secale cereale* L.) cover crop planted at three different dates as well as a fallow treatment at two locations: Dawson, GA, and Headland, AL. Pendimethalin was applied PRE at 1 kg ai/ha across the entire area just prior to planting of the Georgia 03-L peanut variety. Soil samples were collected at three different dates after planting for high-pressure liquid chromatography (HPLC) analysis to determine pendimethalin levels. Peanut yields differed only between location regardless of cover crop residue level with the Headland, Alabama, site averaging 4,272 kg/ha and the Dawson, Georgia, site averaging 2,247 kg/ha. Pendimethalin extraction from soil samples indicated no difference in herbicide recovery between winter fallow systems compared to treatments with cover crops. Weed control ratings taken at 21 and 45 days after planting (DAP) showed greater weed suppression for cover crop systems for an extended period of time when higher levels of cover crop biomass are present. Results of this experiment indicate the inclusion of cover crops in a conservation-tilled peanut system can be a successful alternative to winter fallow systems without reducing peanut yield or herbicide efficacy.

Keywords: Conservation tillage, high-residue cover crops, peanut production

1. Introduction

Peanut offers significant value to agricultural producers in the southeastern United States each year with approximately 530,000 ha harvested in the United States in 2014 [1]. In recent years, time and money savings offered by conservation systems through reduced labor and tillage practices have led to an increase in peanut production under these systems [2–6]. Governmental incentives offered to producers meeting certain criteria pertaining to the practice of conservation tillage have also aided in increasing adoption rates of these practices [7].

In addition to reduced production costs, other benefits of conservation tillage are well recognized throughout agricultural literature, including reduced soil and water loss, increased soil organic matter, improved soil structure, higher-quality stand establishment, and less incidence of disease [8–12]. Cover crop integration into conservation tillage systems further enhances benefits achieved through reduced tillage practices when compared to winter fallow systems [13–16]. Despite the advantages and growing interest, peanut production under conservation tillage systems still lags behind conventional production methods owing to producer concern over yield reduction either through digging losses or through reduced pegging due to cover crop residue impediment [17–19]. Furthermore, the use of cover crops with high biomass may reduce the efficacy of preemergent herbicides and increase producer reliance on postemergent formulations [20–22].

Since the introduction of dinitroaniline herbicides, such as pendimethalin, peanut producers have been integrating this soil-applied, preemergent herbicide into the herbicide regime in order to achieve weed suppression of small seeded annuals [23]. The use of these soil-applied herbicide treatments provides residual activity for several problematic weed species and can reduce the dependency on postemergent herbicide formulations. The growing interest in conservation tillage systems, specifically strip-tillage, in peanut has created an even greater demand for successful herbicide treatment plans due to the loss of weed control from weed seed burial through tillage [24,25].

Pendimethalin is frequently used in reduced-tillage systems due to its high water solubility and low volatility in comparison with other dinitroaniline herbicides [26]. However, there is uncertainty as to whether an acceptable level of weed control can be achieved in peanut systems that include a high level of cover crop biomass due to a physical barrier of residue impeding the movement of the herbicide to the soil surface. Efficacy of pendimethalin, which is tightly sorbed to plant residue, can subsequently be reduced if substantial amounts of the herbicide are intercepted by the cover crop biomass [27,28].

Further questions also remain in regard to cover crop management practices and their role in reducing cover crop interaction with soil-applied herbicides in reduced-till peanut systems. Typical termination practices for cover crops include treating the cover with a nonselective herbicide (glyphosate or paraquat) 2–4 weeks prior to the primary crop plant date and leaving standing residue as a cover [29]. Standing residue will reduce soil and water loss but can hinder planting operations by clogging the planter between the row cover [30]. Mechanically rolling or crimping plant residue, used in conjunction with termination herbicides, is another option for effectively managing cover crops prior to planting [29]. This management system, although less frequently used, increases cover crop termination efficacy with the inclusion of an herbicide while effectively creating a dense layer of residue. This layer of cover crop biomass can reduce soil moisture evaporation, subsequently reducing soil strength in comparison with standing residue, and reduce weed seedling emergence [31,32]. While there are many benefits to rolling cover crop residue, concerns exist in regard to increased interception of preemergent herbicides by a dense horizontal layer of plant matter covering the soil surface.

The objectives of this study were to determine the impact of differing levels of biomass residue on peanut production systems in terms of yield and weed control. Moreover, we hope to determine how herbicide interception is affected in different levels of biomass as well as under different termination management strategies to include standing residue and mechanically rolled residue practices.

2. Materials and methods

Field experiments were conducted from the fall of 2006 to the fall of 2008 at the Hooks Hanner Environmental Resource Center in Dawson, GA, and the Alabama Agricultural Experiment Station's Wiregrass Research and Extension Center (WREC) in Headland, AL. Soil types were mostly a Greenville sandy clay loam (fine, kaolinitic, thermic Rhodic Kandiudults) at the Georgia site and a Dothan fine sandy loam (fine-loamy, siliceous, thermic Plinthic Paleudults) at the Alabama site. Experimental layout was a randomized complete block split-plot restriction design with three replications at each site. The main effect of cover crop residue levels (low, medium, high, or fallow) was determined by planting date. Subplots consisted of cover crop termination practice (herbicide and herbicide plus rolling) and herbicide selection (paraquat and glyphosate).

Three fall planting dates of rye (*Secale cereale* L.) spaced approximately 30 days apart were conducted from October through December at each location for both years. Seeding rates were 100 kg/ha at the Headland and Dawson sites. Cover crops were planted using a Great Plains No-Till[1] drill. Termination of rye and fallow plots was conducted in early May, 3 weeks prior to peanut planting (except at the Dawson site where planting was delayed until June for both years) with either glyphosate at 1.7 kg ai/ha or paraquat at 0.84 kg ai/ha. Aboveground ¼ m^2 biomass samples were randomly taken from all plots just before termination and dried at 60°C to determine the dry weight. Cover crop residue was then either left standing or mechanically rolled prior to planting.

Peanut (cv Georgia 03-L) was planted into a strip-tilled system each spring at a rate of 18 seed/m. Strip-tillage, the predominant choice of conservation systems for peanut farmers, was performed using KMC[2] ripper to prepare a 30- cm-wide seedbed area. Plot size was four 10-m rows on a 91-cm spacing for the Headland location and six 10-m rows on a 91-cm spacing for the Dawson site. Pendimethalin was applied as a preemergence treatment across the experiment at a rate of 1 kg ai/ha each year.

Soil samples were collected from each experiment at 7-, 14-, and 21-day increments after pendimethalin application (except at WREC in 2007 due to an oversight). Four random subsamples were collected and combined for each of the sampled plots. Collection of soil was done with a stainless steel flat scoop to include the upper 2 cm of the soil surface. Samples were wrapped in foil before being placed in plastic bags to reduce herbicide adsorption to the plastic and subsequently stored in a cooler for storage until processing. Prior to storage, gravimetric water content of the soil was determined with a 20-g portion of each sample.

Preparation of soil samples for HPLC analysis was conducted based on procedures described by Potter et al. [26]. Samples (50 g each) were processed through a 2-mm sieve and placed in 250-mL glass bottles for extraction with three repetitions using 50 mL of methanol. After extraction, samples were vacuum-filtered and the extract was reduced using a rotary evaporator system to 5 mL. The extract was then reconstituted to a 10-mL volume with 1 g of the extract subsequently being placed into an auto sampler vial along with 10 μg of 0.5-mg/ml 2-chlorolepedine (an internal standard added by the laboratory prior to analysis). In addition, spray targets (70-mm Whatman cellulose filter paper[3]) collected at the time of pendimethalin application were extracted in 25 mL of methanol and then diluted to a 1:10 ratio. A 1-g sample was then prepared for analysis in the same manner as soil sample extracts. High-pressure liquid chromatography (HPLC) was then conducted by the USDA-ARS Southeast Watershed Research Laboratory in Tifton, GA.

In addition, visual weed control ratings on a 0–100% scale with 0 being no control were conducted at 21 and 45 DAP. Peanut yield was calculated with the middle two rows after digging and harvesting at each site. During the experiment, additional management practices (including insect control and nutrient management) followed the respective state's recommendations for peanut growing practices.

Data analysis was conducted using the GLIMMIX procedure in SAS[4] to compare treatment effects on yield as well as weed control rating comparisons at $\alpha = 0.05$. Non-transformed data were used for yield comparison; however, arc sine transformation was used to improve variance in weed control data.

3. Results and discussion

3.1. Yield

Main effect differences were only noted between locations ($P < 0.0001$) with Headland having greater yields in both years of the experiment with 4,432 kg/ha and 4,112 kg/ha for 2007 and 2008 compared with Dawson yield over treatments at 1,775 kg/ha and 2,718 kg/ha (Table 1). Historically, Georgia's average yield is more than the expected yield for Alabama producers with recent 2014 yields for Georgia (4,600 kg/ha) and Alabama (3,600 kg/ha) reflecting this slight difference [1]. The disparity between annual averages and experimental peanut yields could potentially be attributed to the general trend toward irrigation for peanut production in Georgia as opposed to dryland production in Alabama (172,000 ha and 56,000 ha, respectively, in 2014) [1]. For this experiment, neither site was under an irrigation system for the duration of the growing seasons.

		Yield (kg/ha)				
		Residue Level				Year
		Fallow	Low	Medium	High	Average
	2007	4,441	4,525	4,441	4,319	4,432
Headland[a]	2008	4,268	3,961	3,939	4,279	4,112
	Average	4,355	4,243	4,190	4,299	4,272
	2007	1,553	1,587	1,815	2,147	1,775
Dawson[bc]	2008	2,311	2,401	2,840	3,319	2,718
	Average	1,932	2,733	2,313	1,994	2,243

[a]Yield differences are significant between locations ($P < 0.0001$).

[b]Yield differences are significant between years within location ($P = 0.0143$).

[c]Yield differences are significant between high and fallow residue levels within location for each year ($P = 0.0054$).

Table 1. Yield for 2007 and 2008 for the Headland and Dawson experimental sites.

		Year	
Residue Level	**Time (d)**	**2007**	**2008**
		———μg/g———	
Fallow	7	——	0.2334[a]
	14	0.1074[A]	0.1089[b]
	21	0.0714[A]	0.1085[b]
Low	7	——	0.3234[c]
	14	0.2398[B]	0.1936[a]
	21	0.0911[A]	0.1333[b]
Medium	7	——	0.2348[a]
	14	0.1371[A]	0.0891[b]
	21	0.0633[A]	0.0944[b]
High	7	——	0.2667[ac]
	14	0.1516[AB]	0.0897[b]
	21	0.1198[A]	0.0546[b]

*Values followed by same letter in same year are not significant at $\alpha = 0.05$.

Table 2. Pendimethalin residue recovered through soil extraction process for Headland. *

		Year	
Residue Level	**Time (d)**	**2007**	**2008**
		——————μg/g——————	
Fallow	7	0.5471^{A}	0.1809^{a}
	14	0.3280^{C}	0.2166^{a}
	21	0.3150^{CD}	0.1722^{a}
Low	7	0.4576^{B}	0.3600^{b}
	14	0.4453^{B}	0.2976^{b}
	21	0.3645^{BC}	0.1601^{a}
Medium	7	0.4550^{B}	0.3140^{b}
	14	0.4111^{B}	0.1760^{a}
	21	0.2558^{D}	0.1457^{ac}
High	7	0.4075^{B}	0.3201^{b}
	14	0.3983^{B}	0.1332^{ac}
	21	0.2783^{CD}	0.0890^{c}

*Values followed by same letter in same year are not significant at $\alpha = 0.05$.

Table 3. residue recovered through soil extraction process for Dawson. *

The location and year of interaction were significant ($P = 0.0047$) with 2008 yields being higher than 2007 for Dawson and yields for Headland being higher in 2007 (Table 1). With low rainfall amounts in comparison to historical averages (Figure 1), reduced 2007 peanut yield for Dawson would be expected due to inadequate rainfall [31]. In 2008, yearly rainfall surpassed average annual rain totals with substantial rainfall occurring in the summer prior to harvest at the Dawson location. Headland rainfall was below average for both 2007 and 2008 (Figure 2), but monthly rainfall totals during the growing season were sufficient for above-average yield (Table 1). Overall, Headland peanut yield for both years of the study, regardless of rain total amounts, was considerably greater than average peanut yields across Alabama.

Yield comparison between fallow treatments and rye cover crop treatments within each location indicated a difference in yield between high-residue treatments and fallow treatments at the Dawson site with high-residue treatments having increased peanut yield by 260 kg/ha in 2007 and 1,010 kg/ha in 2008 (Table 1). The increase in peanut yield under high-residue treatments occurred at the Dawson site both years, although no significant increase in biomass residue was noted for 2007 (Table 1; Figure 3). Headland did have differences between residue levels for both years (Figure 3), but no yield differences were noted for the Headland site (Table 1).

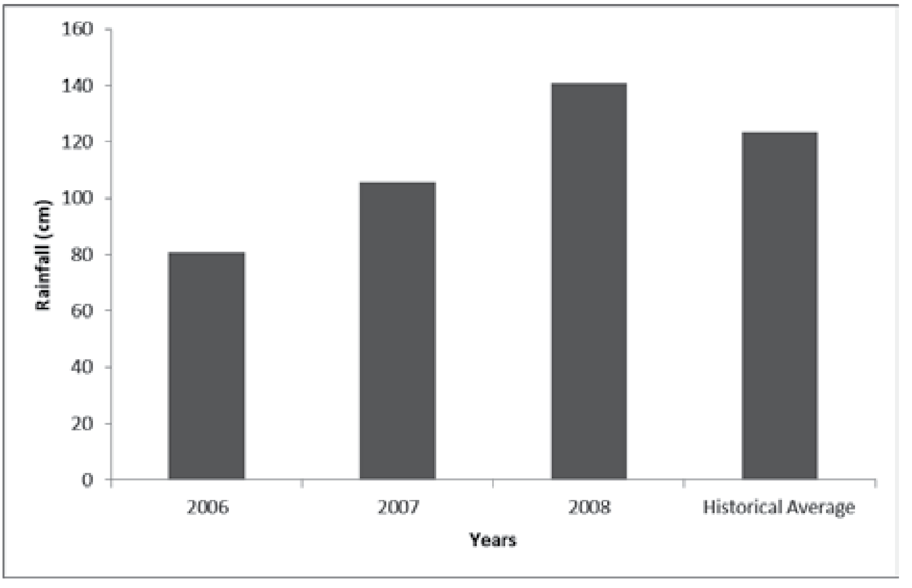

Figure 1. Annual rainfall totals for 2006, 2007, and 2008 along with an historical average over the past 30 years for Dawson, GA.

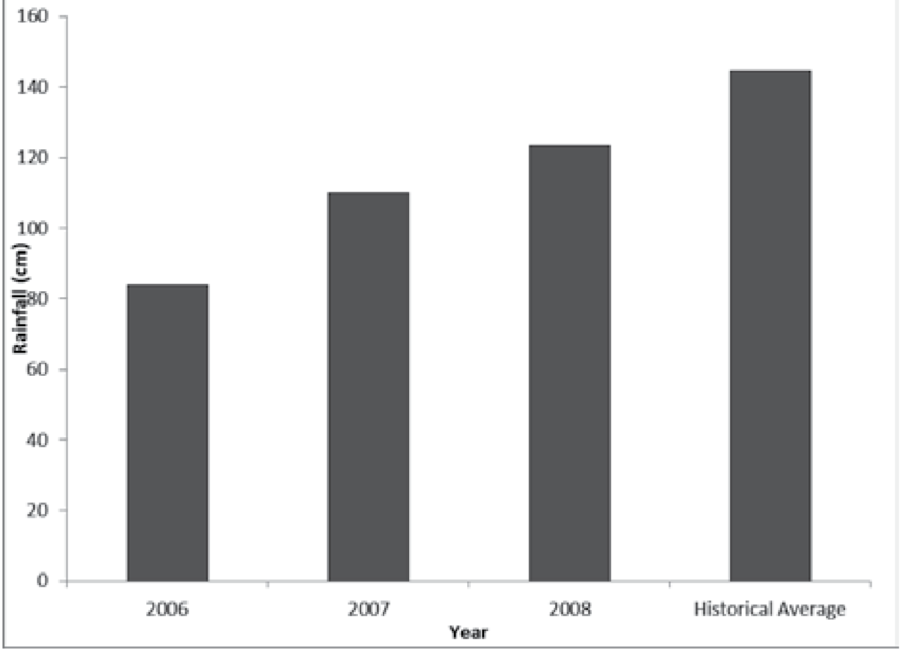

Figure 2. Annual rainfall totals for 2006, 2007, and 2008 along with an historical average over the past 30 years for Headland, AL.

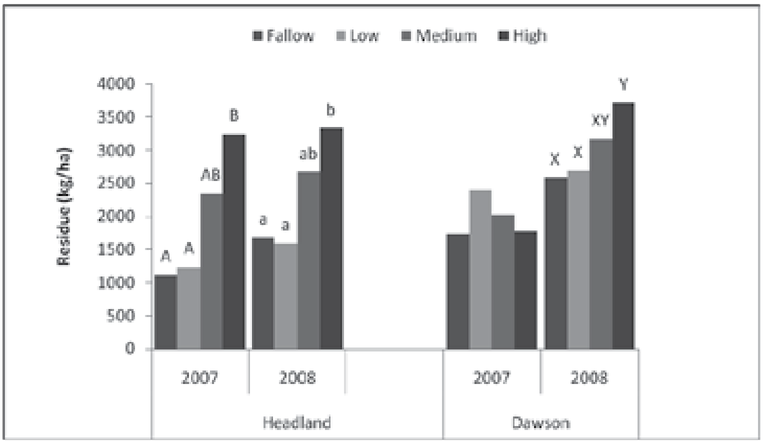

Figure 3. Biomass yield in kg/ha for 2007 and 2008 for the Headland and Dawson experimental sites. Values followed by same letter in same sampling time are not significant at $\alpha = 0.05$.

3.2. HPLC analysis

Analysis of soil extraction samples detected both pendimethalin and its metabolite, pendimethalin alcohol, 4-[(1-ethylpropyl)amino]-2-methyl-3,5-dinitrobenyzl alcohol. The metabolite data are not presented in this study due to trace amounts detected uniformly throughout the samples (<0.05 μg/mL). Recovered pendimethalin is presented by location and year (Figure 4) due to differences detected between these main effects. The general trend in recovery rate indicated the Dawson site, regardless of year, had higher pendimethalin recovery throughout the 21-day sampling period (Figure 4). No difference in pendimethalin recovery was noted between standing and rolled cover crop treatments.

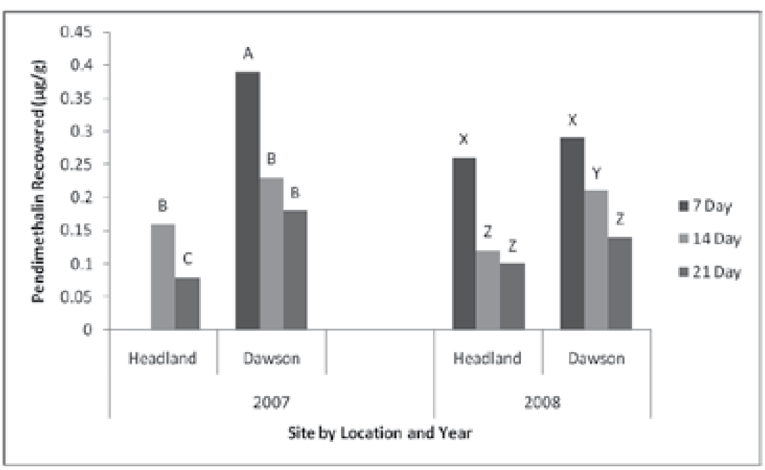

Figure 4. Average pendimethalin residue recovered through soil extraction process by year and location. Values followed by same letter in same sampling time are not significant at $\alpha = 0.05$.

Within location and year, pendimethalin recovery was generally higher for 7-day samples than later sampling dates from expected rapid initial dissipation due to volatilization, photodegradation, microbial metabolism enhanced by warm soil temperatures and soil moisture, and chemical decomposition [21,27,33]. Increases in pendimethalin recovery amount were noted for winter fallow treatments in comparison to cover crop treatments for only the Dawson site in 2007 (Tables 2 and 3). Previous research has reported increased dissipation of preemergence-applied herbicides in cover cropping systems compared to systems with no cover crop [21,34]. In our study, only one site had increased biomass yield for cover crop treatments in comparison to fallow treatments (Figure 5); the limited differences between biomass residues in this study at the Dawson site could potentially mask any effect increased cover crop residue may have on herbicide movement to the soil; however, pendimethalin recovery was not greater for fallow treatments at the Headland site where biomass yields were higher in heavy-residue treatments.

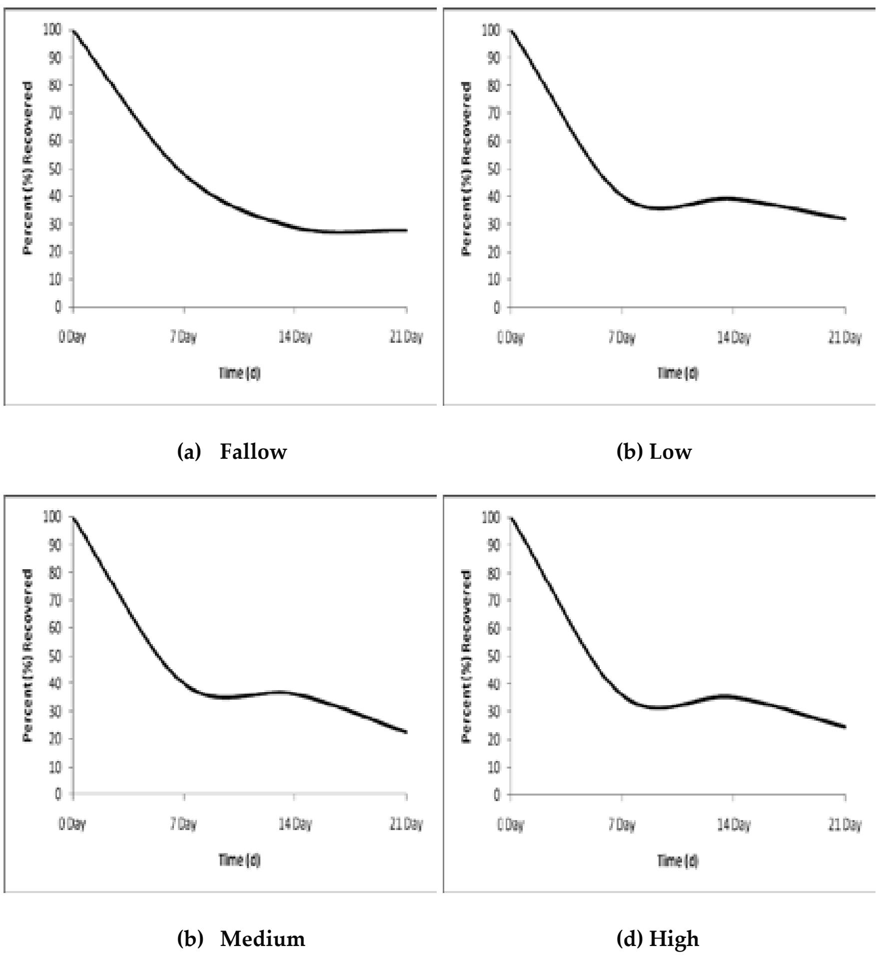

Figure 5. Percent pendimethalin recovered from Dawson during the 2007 growing season at three collection times during a 21-day period after herbicide application.

Although no difference between pendimethalin recovery amounts under different cover treatments was indicated by the results, the amount of pendimethalin extracted from the soil, when viewed as percentages recovered (Figures 5–8), was never greater than 50% of total herbicide applied at the 7-day sampling date. Previous publications investigating pendimethalin dissipation under varied environments have reported half-lives from 10 to 30 days or longer [21,33,36]. These low recovery percentages would suggest herbicide interception, to a degree, in all cover treatments. However, without a comparative pendimethalin dissipation rate under no residue with similar environmental conditions, it is difficult to determine between what proportion of unrecovered pendimethalin was intercepted and sorbed to plant residue and how much was lost through dissipation and degradation.

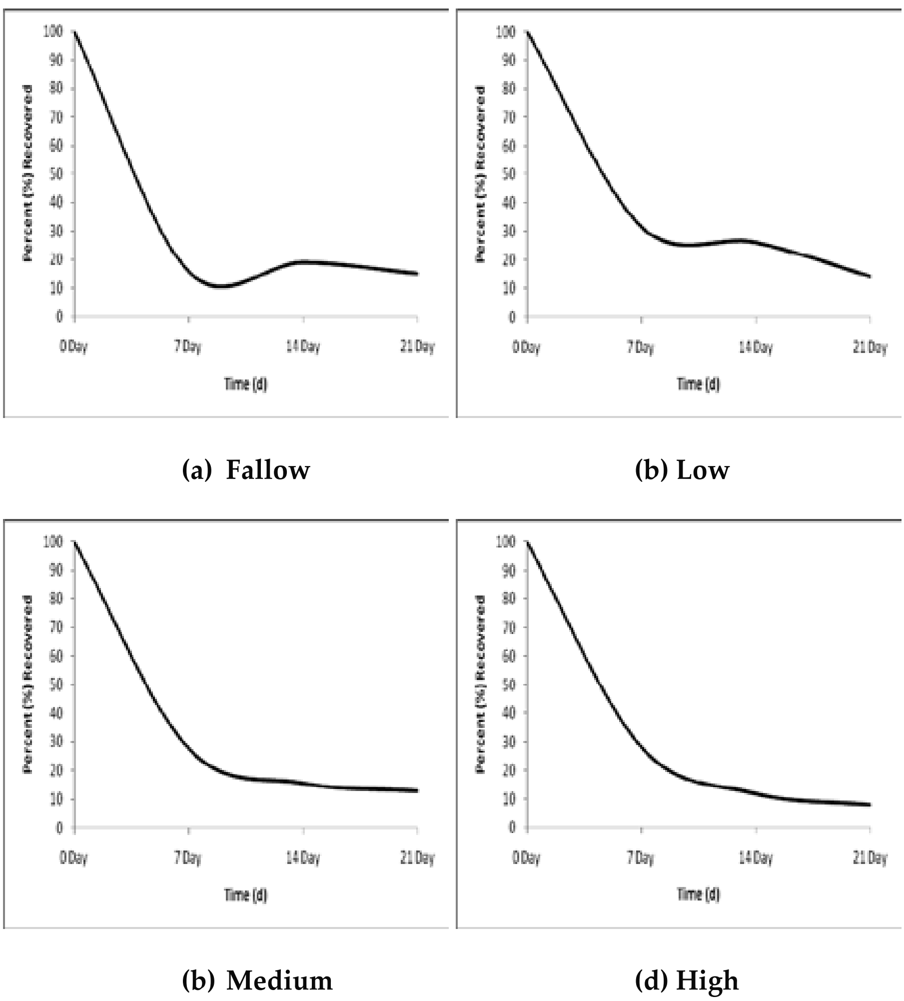

Figure 6. Percent pendimethalin recovered from Dawson during the 2008 growing season at three collection times during a 21-day period after herbicide application.

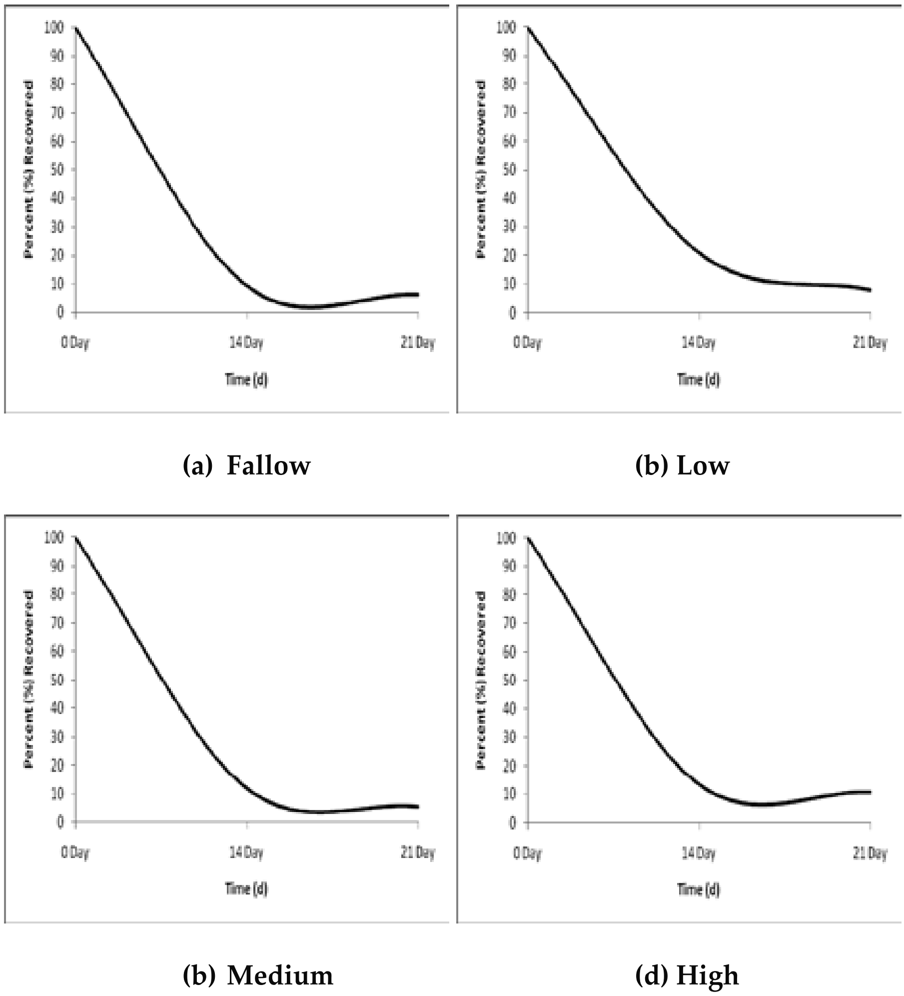

Figure 7. Percent pendimethalin recovered from Headland during the 2007 growing season at two collection times during a 21-day period after herbicide application.

3.3. Weed control

Dominant weed species at the Headland experiment site were nutsedge (*Cyperus* sp.) and smallflower morning glory [*Jaquemontia tamnifolia* (L.) Griseb.]. Weed species present at the Dawson site included Palmer amaranth (*Amaranthus palmeri* S. Watson) and smallflower morning glory. Weed analysis is presented by species at 21 and 45 days after planting (DAP) and averaged over the duration of the experiment due to no difference between years. Residue level was a significant main effect; however, cover crop termination method had no effect on weed control. No interactions were significant for either time period of weed ratings. At 21 DAP, control of smallflower morning glory in Headland was 90% or greater for all residue levels; however, medium- and high-residue treatments had slightly better control at 94%

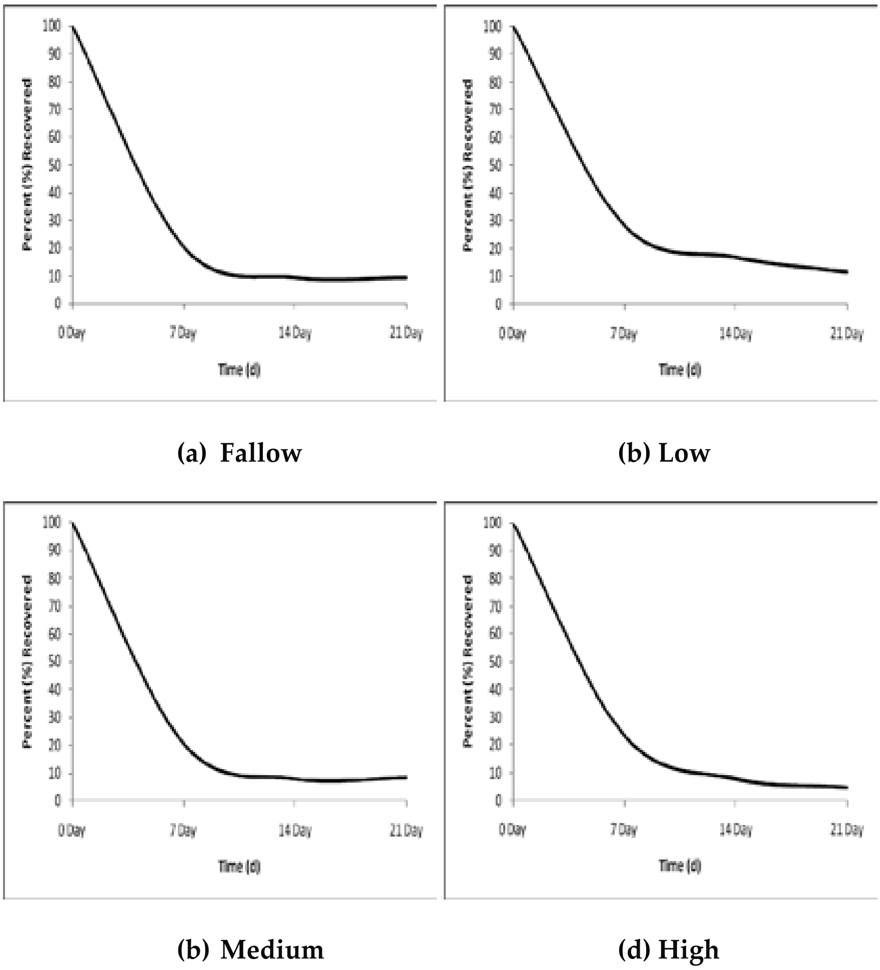

Figure 8. Percent pendimethalin recovered from Headland during the 2008 growing season at three collection times during a 21-day period after herbicide application.

(Table 4). Weed control 2 weeks later indicated suppression of smallflower morning glory by greater than 70% for all treatments, but all cover crop treatments had greater suppression regardless of residue level (Table 4). Nutsedge, like smallflower morning glory, was controlled by 90% or greater at 21 DAP in all residue treatments at Headland, but all cover crop treatments had slightly greater control than fallow treatments (Table 5). At 45 DAP, control of nutsedge was similar to that of smallflower morning glory in that suppression was greater than 70% for all treatments, but greatest weed control was achieved in medium- and high-residue treatments (Table 5).

At the Dawson site, Palmer amaranth control at 21 DAP was greater in all cover crop treatments compared to fallow treatments (Table 6). Control ratings 2 weeks later indicated greater control of this species by high-residue treatments only (Table 6). Smallflower morning glory followed

	21 DAP			45 DAP		
Treatment	**Mean**	***P-value***	**95% CI**	**Mean**	***P-value***	**95% CI**
Fallow	91	———	(90,93)	74	———	(72,77)
Low	93	0.2520	(92,95)	80	0.0052	(78,83)
Medium	94	0.0205	(93,96)	86	<0.0001	(84,90)
High	94	0.0202	(93,95)	83	<0.0001	(81,86)

Table 4. Weed control in Headland of smallflower morning glory by residue treatment in comparison with fallow treatment 21 and 45 days after planting (DAP).

	21 DAP			45 DAP		
Treatment	**Mean**	***P-value***	**95% CI**	**Mean**	***P-value***	**95% CI**
Fallow	90	———	(89,91)	74	———	(72,77)
Low	94	0.0002	(92,96)	78	0.0814	(76,80)
Medium	95	<0.0001	(94,97)	82	<0.0001	(82,87)
High	95	<0.0001	(94,96)	81	<0.0001	(81,86)

Table 5. Weed control in Headland of nutsedge by residue treatment in comparison with fallow treatment at 21 and 45 days after planting (DAP).

a similar trend for both the 21 and 45 DAP control ratings as Palmer amaranth. The first rating revealed greater suppression by all cover crop treatments and the subsequent control rating indicated higher suppression for medium- and high-level cover crop systems (Table 7).

	21 DAP			45 DAP		
Treatment	**Mean**	***P-value***	**95% CI**	**Mean**	***P-value***	**95% CI**
Fallow	51	———	(46,57)	62	———	(55,69)
Low	93	<0.0001	(88,98)	60	0.9499	(52,67)
Medium	94	<0.0001	(89,99)	72	0.1424	(65,79)
High	94	<0.0001	(89,99)	60	0.0061	(71,86)

Table 6. Weed control in Dawson of Palmer amaranth by residue treatment in comparison with fallow treatment at 21 and 45 days after planting (DAP).

	21 DAP			45 DAP		
Treatment	**Mean**	***P-value***	**95% CI**	**Mean**	***P-value***	**95% CI**
Fallow	54	———	(48,61)	63	———	(56,70)
Low	95	<0.0001	(90,99)	84	0.2143	(62,75)
Medium	95	<0.0001	(89,99)	76	0.0093	(69,82)
High	96	<0.0001	(89,99)	69	<0.0001	(77,90)

Table 7. Weed control in Dawson of smallflower morning glory by residue treatment in comparison with fallow treatment at 21 and 45 days after planting (DAP).

Previous research has suggested that the use of cover residue could potentially decrease the efficacy of preemergent herbicides and, subsequently, reduce crop yield under high-residue cover cropping systems [21,27]; while other researches have indicated that cover crops used in conjunction with PRE herbicide applications achieve similar weed control as peanut systems that utilize both PRE and POST herbicides [37]. The results of this experiment suggest that the use of cover crops, at any level of residue, can be viewed as a feasible alternative to fallow systems without increased herbicide sorption or reduced peanut yield. Moreover, the use of these cover crops when higher levels of residue are achieved may even offer greater weed suppression for a longer period of the growing season, providing producers with a cost-effective means to combat weed infestations without an overdependence on early postemergent herbicide applications.

4. Sources of materials

[1] Great Plains No-Till drill, Great Plains Mfg., Inc., 1525 East North Street, Salina, KS 67401.

[2] KMC ripper, Kelly Manufacturing Company, 80 Vernon Drive, Tifton, GA 31793.

[3] Whatman cellulose filter paper, Whatman Inc., 800 Centennial Avenue, Piscataway, NJ 08854.

[4]SAS software, version 9.1, 2002–2003, Statistical Analysis Systems Institute Inc. Cary, NC 27513.

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Chapter 6

Herbicide Use and Increased Scourge of *Parthenium hysterophorus* in Vegetable Production in Trinidad and Tobago

Puran Bridgemohan, Wendy-Ann P. Isaac, Raymond Macoon and Cherrianne Johny

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61732

Abstract

This chapter highlights a survey of vegetable-producing areas to determine the occurrence, distribution and importance of *Parthenium hysterophorus* in Trinidad. The weed can significantly reduce crop yields and quality due to its aggressive growth habit, competitiveness and allelopathic interference. Due to its invasive capacity and allelopathic properties, *Parthenium hysterophorus* has the potential to disrupt the natural ecosystem and threaten the biodiversity. It is a difficult weed to manage, and a wide variety of methods, starting with prevention and containment, is necessary to reduce the incidence and spread of this weed. An integrated approach using cultural, physical, chemical and biological techniques is necessary to be successful. Focus is made on specific herbicides currently being used to manage this weed in vegetables. Despite the negative impact of this weed on the biodiversity, this chapter also explores the potential of the beneficial properties of *Parthenium hysterophorous* as a mechanism of management.

Keywords: Vegetable production, *Parthenium hysterophorus*, herbicide use, integrated approach

1. Introduction

Parthenium hysterophorus L., commonly called barley flower [1] and white-head or white-top [2] in the Caribbean, is considered a noxious weed. The plant exhibits wide ecological amplitude, and invades and competes with all types of crops, especially vegetables, with substantial losses in yield [3]. The weed has become problematic in early orchard establishment, and ornamental and greenhouse production, and also invades industrial areas including airport lay-bys.

The weed displays characteristics of profuse seeding ability, photo and thermal insensitivity, non-dormancy, high germination and growth rate and low photorespiratory rate, enormous seed bank, rapid spread and colonization and extreme adaptability in a range of habitats [4] and has spread within the last two decades to all Commonwealth Caribbean countries [2]. It is among the top ten worst weeds of the world and has been listed in the global invasive species [5]. It is now considered one of the worst weeds because of its invasiveness, potential for rapid spread, economic and environmental impacts, its high adaptability to almost any type of environmental conditions and high losses in crop yield and its direct contact with plant or plant parts [5]. As a C3 weed, *Parthenium* uses one of the two types of photosynthetic pathways, which responds to higher levels of CO_2 [6]. This enables it to grow more rapidly and become more competitive through increased leaf size, seed size and production, plant toxicity and pollen production [6].

The weed is predominant in the major vegetable-growing areas of Trinidad and has been shown to be effectively controlled by dinitroanilines, e.g. butralin (4- (1, 1-Dimethylethyl)-N-(1-methylpropyl)-2, 6-dinitro-benzenamine) in eggplant (*Solanum melongena* L.), and by the amide herbicide, diphenamid (N, N-Dimethyl-2, 2-diphenyl-acetamide) in cabbage (*Brassica oleracea* var. *capitata* L.) [7]. In pot studies, glufosinate ammonium was shown to give good levels of control [6, 68]. The weed has shown resistance to bipyridylium herbicides in Trinidad and other Caribbean territories and has become dominant on lands where these chemicals are used intensively [2; 6]. The plant has the ability to survive carbohydrate depletion approach to control with rapid regrowth soon after mechanical control [7, 8, 9].

P. hysterophorous is deemed a noxious weed in Australia [10] and India [3], where it causes severe skin allergies [11], fever and asthma, and often death among the population [12]. Although no cases of allergies or death have been reported in Trinidad [7], many farmers have, however, reported increased asthma attacks.

In the major vegetable production areas of Trinidad and Tobago, the weed was identified as early as 1956. However, it was not of any significance until the 1960s when the use of paraquat (1, 1′-dimethyl-4-4′-bipyridinium ion) and diquat (6, 7-dihydrodipyrido (1, 2- a: 2, 1-c) pyrazinedium ion) became widespread.

2. Biology and ecology

The genus *Parthenium* comprises 15 species, all of which are native to North and South America. *P. hysterophorus* L. has a native range in the neo-tropics from Mexico to Argentina. It is thought that the species originated in the region surrounding the Gulf of Mexico or in central South America, but is now widespread in North and South America and throughout the entire Caribbean [6].

P. hysterophorus L. (family *Asteraceae*) is an aggressive and noxious annual herbaceous weed that has spread from tropical America to various tropical and subtropical parts of the world. It is included in the International Union for Conservation of Nature (IUCN) Global Invasive Species database and is rated one of the most serious weeds of the 20th century. This may be attributed mainly due to its vigorous growth and high fecundity in habitats varying from hot and arid, semi-arid to humid and from low- to middle- to high-altitude regions.

P. hysterophorus is an annual herb with a tendency to be perennial, growing erect up to 2 m in height. It has a deeply penetrating root system with a stem that is branched and covered with hairy structures or trichomes, bearing dissected pale green leaves that are lobed and hairy. Leaves vary from 6 to 55 per plant and are irregularly dissected and bipinnate, having small hairs on both sides. Trichomes are considered storehouses for one of the toxic chemicals found in the weed known as parthenin [14].

Flower heads are creamy white, about 4 mm across, arising from the leaf fork and forming a capitula. Flowering usually occurs one month after germination with each flower containing five seeds, which are small (2 mm), wedge-shaped, brown to black in colour and bear two thin white scales. Pollen grains are produced in clusters and are pollinated by wind. A single plant can produce around 15,000 seeds or even up to 100,000 seeds. Seeds are mainly dispersed through water currents, animals and the movement of vehicles, machinery, livestock and stock feed, and to a lesser extent by wind. Seeds can remain viable for long periods and are capable of germinating as long as moisture is available [10].

The ideal conditions for growth are high moisture content, high humidity and a temperature of around 25°C. However, it can grow under a wide range of environmental conditions with soil moisture being the only limiting factor for germination and growth. It can grow under a wide range of soil pH (2.5 to 10.0) [15]. Additionally, it grows well in areas where annual rainfall is higher than 500 mm. In Trinidad, this weed grows on abandoned lands, along highways and roadsides, in drains, gardens, plantations and vegetable crop plots. It colonizes disturbed sites very aggressively, possesses allelopathic properties and has no documented natural enemies like insects or diseases.

3. Phytochemical analysis of *P. hysterophorus*

Phytochemical analysis of *P. hysterophorus* has revealed that plant parts such as leaves, trichomes, inflorescence and pollens contain toxins such as sesquiterpene lactones (SQL), kaempferol, p-coumaric acid and caffeic acid [16; 17]. These phytochemicals are highly concentrated in the leaves. The SQLs, namely parthenin and coronopilin as well as hymenin and ambrosin, are present in the trichomes of the leaves and stems and are responsible for causing various allergies such as dermatitis, hay fever, asthma and bronchitis. It is also responsible for the inhibition of pasture germination and growth. The allelopathic effect is due to allelochemicals such as phenolic acids and SQLs [18; 19]. Other phytotoxic compounds or allelochemcials are hysterin, flavonoids, such as quercelagetin 3,7-dimethylether, 6-hydroxyl kaempferol 3-0 arabinoglucoside, fumaric acid, p-hydroxy benzoin and vanillic acid, anisic acid, p-anisic acid, chlorogenic acid, ferulic acid, sitosterol and other alcohols [17; 20].

4. Incidence of *P. hysterophorus* in vegetable crops

Weed surveys in the main vegetable production areas were conducted in both dry and wet season using seven quantitative measures [21–24] *viz.* visual estimates (VE), abundance (Ap), density (Dp), percentage frequency (Fp), relative dominance (RDi), relative density (RDp) and relative frequency (RFp), which were used to compute the Importance Value Index (IVI) of *P. hysterophorus*.

$$IVI = RDi + RDp + RFp$$

The IVI allowed for comparisons between seasons and years and among crops. However, it does not necessarily represent losses in crop production caused by the weed as crops vary in their competitive ability. The level of losses due to the presence of the weed in various vegetable crops was assessed and the economic importance of the weed determined. Irrespective of the visual estimate (VE) of *P. hysterophorus* infestations in the wet season (Table 1) and dry season (Table 2), the frequency (Fp) in both seasons was greater than 50%.

Crop	VE	Fp	IVI
Cauliflower[1]	50	90	417.1
Cauliflower[2]	10	70	262.5
Tomato[3]	25	100	274.1
Tomato[4]	50	90	430.0
Tomato[5]	75	100	562.5
Cabbage[6]	40	100	379.9
Cabbage[7]	50	100	974.7
Patchoi	40	100	382.2
Sweet Pepper	25	50	265.4
Hot Pepper	25	50	273.5
Spinach	30	90	358.0
Okra	100	100	880.0
Fallow Field	100	100	910.0
Mean	48	87.5	489.9
S.E. (+/−)	7.85	5.2	72.17

2 hand weedings and no herbicide[1]; 1 hand weeding and 1 herbicide application[2]; 2 hand weedings and 1 herbicide application[3]; 3 hand weedings and no herbicides[4]; 2 hand weedings and no herbicide[5]; 2 hand weedings[6]; 1 hand weeding[7]. (VE – visual estimate; Fp – frequency; IVI – Importance Value Index)

Table 1. Incidence of *P. hysterophorus* in various vegetables during the wet seasons.

Crop	VE	Fp	IVI
Squash	90	100	674.9
Tomatoes	75	100	836.4
Cabbage	10	50	360.0
Spinach	25	100	365.6
Bodie Bean	10	100	207.8
Cauliflower	10	50	215.8
Mean	36	83	443.4
S.E. (+/−)	2.45	2.07	6.5
(VE – visual estimate; Fp – frequency; IVI – Importance Value Index)			

Table 2. Incidence of *P. hysterophorus* in various vegetables during the dry seasons.

There was no significant difference in the mean Importance Value Index (IVI) of *P. hysterophorus* for the wet (489.9) and dry (443.4) seasons. Also, variations between seasons were minimal under c = similar levels of weed management; cabbage in the wet season had an IVI of 379.9 and in the dry season 360.0; cauliflower 262.5 (wet) and 215.8 (dry) and spinach 358.0 (wet) and 365.6 (dry).

In the wet season (Table 1), there were variations within the same crops due to different levels of weed management, e.g. cauliflower with two hand weedings and no herbicides had a higher IVI (417.1) than a crop of similar age with treatments of one hand weeding and pre-emergence herbicide (262.5); similar trends for tomato and cabbage were observed at the same growth stage, but under different levels of weed management. The application of pre-emergence herbicides reduced the IVI for *P. hysterophorus* by 40 to 50% over the treatment of two hand weedings and no pre-emergent herbicide.

Crops with shrub-type architecture, e.g. hot and sweet peppers, had no competitive plant height advantage over leafy vegetable crops under similar levels of weed management. Both types of crops had an IVI below the mean value recorded for the wet season.

In both the wet and dry seasons, the IVI of leafy vegetable crops was lower than the mean IVI. This is due mainly to the close spacing used at planting and the intensity and thoroughness of the hand-weeding operations practised by the farmers.

A field prepared for planting, but subsequently abandoned, showed an IVI of 910.0 (wet season) and gave an indication of the weed's dominance. The high IVI (880.0) for okra in the wet season was due to the wide spacing as well as the absence of any weed management operations. The *P. hysterophorus* seedlings were the same height as the crop (15–20 cm).

In the fields surveyed, adequate irrigation facilities were available to all farmers during the dry season. Adequate water supply was the main factor determining the lack of shift in *Parthenium* populations between seasons.

4.1. Incidence of *P. hysterophorus* during different seasons

There was no significant difference between visual estimates (VE) for *Parthenium* in the wet and dry seasons in the Aranguez district (Table 3) or for the major vegetable-growing areas of Trinidad (Table 4). Visual estimates in the range of 25 to 60% can be considered as moderate infestations [23].

There were no changes in abundance (Ap) between seasons. *Cyperus rotundus* (L.) #CYPRO, 'the world's worst weed' [22], is a serious weed in vegetable crops in India with an abundance of 2.7–9.6 [23]. The Ap for *P. hysterophorus* fell well within this range in both seasons.

Wet season density (Dp) in Aranguez (5.24) did not differ significantly from that of other vegetable-growing areas (5.6). The Dp for *Parthenium* emphasizes predominance of this weed in both seasons. Frequency (Fp) was over 80% in both seasons. Weeds occurring in the frequency levels 75–100 are serious weeds that require some level of control [23].

The IVI indicated that there were no shifts in the *P. hysterophorus* population between seasons (Table 3). Also, there was no significant difference between IVIs for wet season in the major vegetable-growing areas of Trinidad (Table 4). These findings indicate that *P. hysterophorus* is a serious problem in all the major vegetable-growing areas in Trinidad, especially where the IVI is even greater for the dry season.

5. Crop loss assessment

Parthenium has caused significant losses to the vegetable production in both seasons in almost all Caribbean islands. Most farmers reported that the weed had no effect on the yield of solanaceous crops, if it was effectively controlled while the crop was in the early vegetative stage or prior to flower initiation. However, if weed control was poor, they observed yield reductions of 25 to 30% for the wet season and 20 to 25% for the dry season.

Farmers found that the presence of the weed within or around the field can result in a reduction of the market yield of cabbage and cauliflower. It was observed that damage to marketable curds of cauliflower caused by the larvae of *Plutella xylostella* (L.) (Lepidoptera: Yponomentidae) varied between 75 and 100%. Apparently, the adult pest found *P. hysterophorus* to be a suitable 'resting site'. On nursery beds, failure to remove *P. hysterophorus* seedlings at 3- to 5-day intervals on a regular schedule resulted in a 75 to 100% loss of healthy and vigorous vegetable transplants.

Parameter	Season	
	Wet (October–November)	Dry (February–April)
VE	47.69	36.66
Ap	5.77	5.25

http://dx.doi.org/10.5772/61732

Parameter	Season	
	Wet (October–November)	Dry (February–April)
Dp	5.24	3.99
Fp	87.69	83.3
RDi	58.88	56.8
RDp	415.61	340.0
F4RFp	66.31	61.36
IVI	489.99	443.43

(VE – visual estimate; Ap – abundance; Dp – density; Fp – frequency; RDi – relative dominance; RDp – relative density; F4RFp – relative frequency; IVI – Importance Value Index)

Table 3. Incidence of *P. hysterophorous* during wet and dry seasons for Aranguez, Trinidad.

Parameter	Season			
	Wet (October–December)		Dry (February–April)	
	Mean	S.E.	Mean	S.E.
VE	43.87	1.78	35.58	1.23
Ap	7.46	1.11	15.50	1.67
Dp	5.6	0.66	15.04	1.68
Fp	65.32	14.96	88.4	1.15
RDi	53.02	9.04	44.4	1.81
RDp	412.0	37.46	284.73	4.51
F4RFp	58.43	5.9	59.48	1.03
IVI	491.19	37.92	378.5	4.76

(VE – visual estimate; Ap – abundance; Dp – density; Fp – frequency; RDi – relative dominance; RDp – relative density; F4RFp – relative frequency; IVI – Importance Value Index)

Table 4. Incidence of *P. hysterophorous* during wet and dry seasons for the major vegetable-growing areas of Trinidad

6. Competitive effect of *Parthenium* on selected crops

A high density of *P. hysterophorus* resulted in the total loss of one tomato crop (cv. Calypso), where failure to remove the weed before flower initiation stage or weed had a V.E. of 100% and IVI > 800. *P. hysterophorus* was the only weed present in the field at the time of the survey and was 75 to 100 cm tall and flowering profusely. The farmer had applied paraquat at the pre-plant stage of the crop.

Failure to plant lettuce and celery on *weed*-free plots can result in a 50 to 60% mortality of the transplants. When early hand weeding at 10- to 14-day intervals was not done, mortality in excess of 75% was observed.

No significant reduction in yield was reported by farmers for vining crops, e.g. pumpkin, squash, or cucumber and staked bodibean which withstood the weed competition. However, early hand weeding was essential for bush-type cowpea bodi to prevent yield reductions by 25 to 50%.

Studies conducted on soil amended with unburnt and burnt residues of *P. hysterophorous* revealed phytotoxic effects on test crops, which was attributed to the presence of phenolics [17]. Parthenin has also been reported as a germination and radicle growth inhibitor in several plant varieties and it enters the soil through decomposing leaf litter [17; 19].

The reduction in crop yield and quality is probably due to the competitive ability and allelopathic potential of *Parthenium*. It is noted that although the weed is a C_3 plant, low carbon dioxide compensation concentration and photorespiratory rate were observed [24]. This was attributed to the activity of PEP carboxylase. The weed is described as having a lush growth and a high survival potential. It has been reported that *P. hysterophorous* produced allelopathic compounds that influenced pollen germination and tube growth in solanaceous and bean crops, where yield reductions of 27 to 73% were observed [25; 26].

7. Weed economic assessment

An economic analysis was performed on *P. hysterophorous* involving a cost–benefit analysis, where several variables were inputted onto a toolkit developed by Landcare Research, New Zealand [27]. The toolkit was developed in an attempt to assign monetary values, where possible, to specific variables in order to conduct cost–benefit analyses on different management options for the control of the weed using four management options *viz.* 'Do Nothing' (DN), 'Current Management' (CM), 'Integrated Management Approach' (IMA) and 'Exploitation of Benefits' (EB). The outcome of the toolkit ranked the management options in terms of Net Present Value (NPV), Benefit-Cost Ratio (BCR) and Cost-Effectiveness (CE). The analysis was done on four proposed management options in order to determine the best suitable one for the control of this invasive weed (Table 5).

Over time, the DN option had the most rapid increase in population, followed by the EB and then by CM. The IMA displayed the slowest increase in the invasive population during that time.

Quantifying the benefits for each management option proposed for the control of *P. hysterophorous* (white-top) took into consideration the value per unit for several categories for benefits and costs of each management option. Benefits are described as the monetary or non-monetary gain received because of an action taken or a decision made. The benefits included agricultural and research crops, human health and biodiversity. The human health variable accounts for visits to the doctor for conditions related to the effect of *Parthenium* such as skin inflammation, eczema, asthma, allergic rhinitis, allergic bronchitis and burning and blistering of the eyes (Table 6).

Management Option	Description
Do Nothing (DN)	· no weed control · allow weed to grow and spread · population density (6% of the carrying capacity)
Current Management (CM)	· maintain the *status quo* of the weed population · chemical control of the weeds (paraquat and glyphosate post-emergence)
Integrated Management Approach (IMA)	· chemical control · manual · mechanical control methods (hoe and plough, cutting and hand weeding or uprooting of weeds)
Exploitation of Benefits (EB)	· determine benefits – medicinal value, enhancement of crop productivity · bioremediation (heavy metals) · dyes and handicraft production

Table 5. Description of the proposed management options for the control of *Parthenium hysterophorus*.

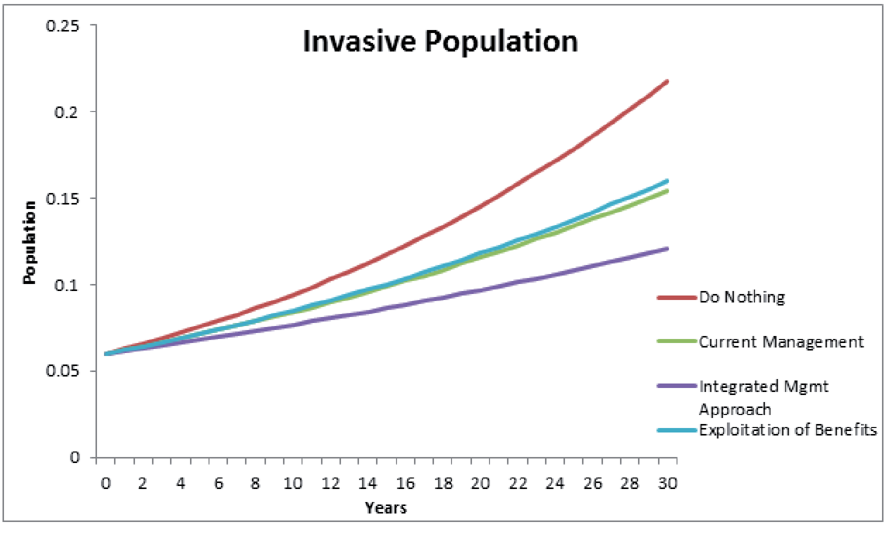

Figure 1. The trend of the invasive population for each management option.

The costs associated were different for each management option and included labour and capital costs (tool, safety gear and machinery). Herbicide cost included the purchase of chemicals, based on market prices, and machine service cost included the servicing of the whacker on a per-service basis (Table 6).

The Net Present Value (NPV) represents the overall net benefit of a project to society. The Benefit Cost Ratio (BCR) is the ratio of the NPV of benefits associated with an activity, relative to the NPV of the costs of the same activity. The discounted future costs and benefits to present value used a discount rate of 5% and the project length is assumed to be 10 years. Cost-effective

(CE) analysis is an approach often used to rank intervention options when monetary benefits cannot be derived from key categories in a given project. CE is the NPV of the monetized costs of the intervention divided by the effectiveness of the project option measured in physical units. The smaller the CE ratio, the greater is the cost-effectiveness of an intervention.

				Units For Initial Period			
	Category	Units	Unit Value ($/units)	Do Nothing	Current Management	Integrated Mgmt Approach	Exploitation of Benefits
Benefits	Agricultural Crops	$/kg	10.00	335	335	335	335
	Research Crops	$/kg	25	8,087	8,087	8,087	8,087
	Human Health	$/report	200	24	24	24	24
	Biodiversity	$/m^3	50	5,280	5,280	5,280	5,280
Costs	Labour	$/day	200	0	36	72	270
	Initial Capital Cost	$/unit	1	0	1,775	8,670	9,000
	Herbicides	$/litre	20	0	16	16	0
	Machine Service	$/service	200	0	0	3	0
	Research	$/hour	30	0	0	0	600

Table 6. Costs and benefits for each management option.

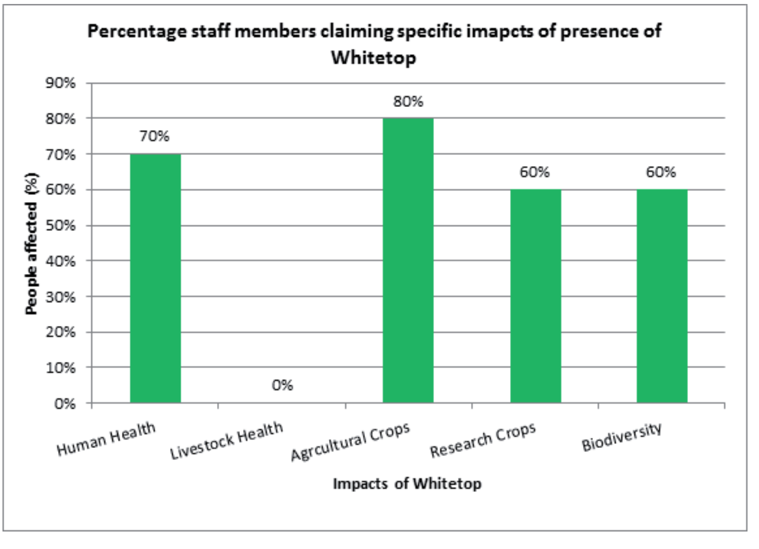

Figure 2. Percentage of Waterloo Research Centre (WRC) staff affected by the impact of *Parthenium* (white-top).

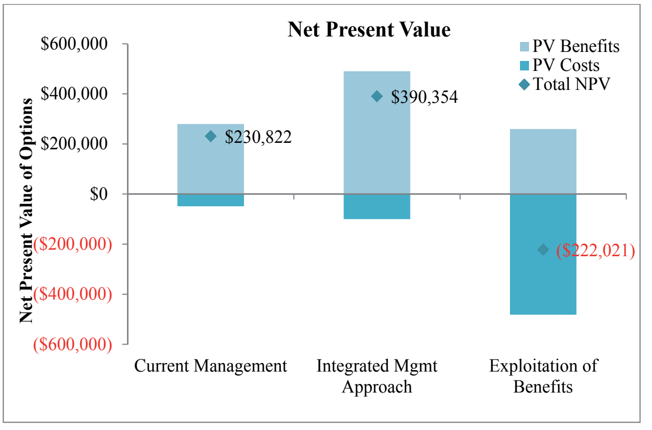

Figure 3. Net Present Value for the management options for the control of *Parthenium*.

Scenario	Total NPV	NPV Rank	BC Ratio	BCR Rank	CE ($/Metric)	CE Rank
Do Nothing	$0	3	1.0	3	0	-
Current Management	$230,822	2	5.7	1	−1,218	1
Integrated Management Approach	$390,354	1	4.9	2	−1,668	2
Exploitation of Benefits	−$222,021	4	0.5	4	−24,079	3

(NPV – Net Present Value; BCR – Benefit Cost Ratio; CE – Cost-Effectiveness)

Table 7. Summary of the Net Present Value, Cost Benefit Ratio and Cost-Effectiveness rankings for the four management options for the control of *Parthenium*.

The cost–benefit analysis for the four different management options disclosed that the CM option yielded the greatest benefit for each dollar of costs and thus was most efficient on funds (Figure 3). The CM option also ranked first in cost-effectiveness being the option with the least cost per physical unit of benefit (Table 6 and 7). The 'Integrated Management Approach' (IMA) ranked first in NPV. Therefore, this option yielded the most benefit to society in terms of managing the spread of *P. hysterophorous*, without considering the costs associated. Both approaches appear to be better than the DN option. The EB option, however, proved to require the largest investment, to yield the least benefits per dollar spent and be the least cost-effective management option compared to the other options.

8. Management of *Parthenium hysterophorus*

Because of its negative impact on the natural and agroecosystem, it is necessary to manage *P. hysterophorus* before it sets seed and continues to spread. There are several methods documented for managing this weed. These include preventative, mechanical, cultural, chemical and biological control methods and even includes potential management by proper utilization of the positive attributes of *P. hysterophorus*. However, effective management of *P. hysterophorus* requires an integrated approach. The following outlines some of the successful and potential best management practices used throughout the Caribbean and the rest of the world.

8.1. Prevention and containment

The best methods of weed management is prevention and containment. *P. hysterophorus* usually completes its life cycle in 4 weeks; so, it is important to manage the weed before the plant flowers or sets seed and when infestations are small – do not allow the weed to be established. The seeds of *P. hysterophorus* can be spread through flowing water or can be blown by the wind, which further makes prevention of spread difficult. The seed can also stay for years in the soil seed bank and the continuous removal of the weed is required until the seed bank is depleted.

Difficulties in the preventive method could be further exacerbated through the easy spread of seeds through vehicles, machinery, the trading and transport of goods, animals grazing on infested fields and the transportation of sand, soil and compost from infested areas to uninfested areas. These are potential risks for further spread and hence should be controlled through an adoption of quarantine measures involving the adoption of inspection and wash-down procedures.

8.2. Mechanical control

Manual removal of *P. hysterophorus* by hand weeding before flowering and seed setting is the most effective method, but it is not necessarily practical or economical particularly where there are large infestations. This method, however, may pose a health hazard from allergic reactions and a danger that mature seeds will drop and increase the area of infestation.

Other mechanical treatments, such as grading, mowing, slashing and ploughing, are also considered inappropriate since they may also promote seed spread as well as rapid regeneration from lateral shoots close to the ground [28; 29]. Ploughing the weed before the plants reach the flowering stage may be effective. Although burning is not promoted as a control strategy, it has been used to control the first flush of emergent weeds at the beginning of the rains in Australia but is only considered a short-term control measure [30]. Burning has been shown to create open niches in the landscape, into which larger number of *Parthenium* seeds are able to germinate in the absence of vegetation.

8.3. Cultural control

This is considered one of the most cost-effective methods, but it is practical only on small farms or where it is part of an integrated weed management strategy. Farmers have used almost every conceivable practice to reduce the infestation on their holding such as hand weeding, brush cutting and even digging out the weed. In all cases, there is a rapid regrowth from both stumps or re-emergence from the existing seed banks.

Mulching using plant stubble is often used for general weed control, but this is on a limited scale. However, this has not proven to be effective in areas where the seed bank is predominantly *P. hysterophorous* and the soil is moist. This condition stimulates germination and growth through the layer of mulch. Black plastic sheets may also encourage weed germination as the heat produced and the moisture conserved by plastic mulches favour weed seeds germination. And, as a result, weed control is more effective in the solarized plot than in the non-solarized plot. Mulch can not only control weeds but can also affect seedling growth adversely as in the case of onions [31]. Grass clipping mulch has been found to boost the growth of the other broadleaf weeds.

The use of pre-emergence herbicides (pendimethalin, oxyfluorfen or alachlor) and a post-emergence herbicide (propaquizafop) in combination with cultural practices such as hand weeding or black polythene mulch has been shown to be effective. The pre-emergent application of oxyfluorfen followed by soil covering with black polythene mulch recorded the least weed count, dry weight of weeds, higher weed control efficiency and favoured the head initiation, early yield, fresh weight and dry weight of heads and highest economic yield, which was at par with treatment with pendimethalin followed by black polythene mulch [30].

On farms where the soil seed bank was dominated by *P. hysterophorus,* it was observed that mulching coupled with manual weeding during land preparation or ploughing would suppress growth and development of weeds including *P. hysterophorus* and enhance yield of tomato [31].

Other cultural methods include the use of competitive cover crops (*Mucuna pruriens, Arachis pintoi* and *Desmodium hysterophorus*), self-perpetuating competitive plants such as *Cornus sericea, Tagetus erecta* (marigold) or smother crops (*Vigna unguiculata*).

8.4. Chemical control

It is important that *P. hysterophorous* be sprayed early before flowering and seed set. Farmers should scout their fields regularly to check for escaped or untreated isolated infestation. Vegetable farmers prefer a rapid knock-down of weeds before they plant or do cultural control and work towards weed-free plots. Repeated spraying may be required even within a single growing season to prevent further seed production. In this regard, their approach is to use a single herbicide with a broad-spectrum application with the intention to rid the field of grasses, broadleaves and sedges. The most commonly used herbicide over the last 70 years in the Caribbean has been paraquat and diquat. These herbicides work very well and usually give very quick control of most weeds, but sometimes cause severe drift damage. It has been accepted that the overuse of this chemical over the years, in addition to the *P. hysterophorous* metabolic pathways [4; 5; 6], has developed resistance to paraquat and has established the predominance of the weed.

Several herbicides (Table 8) have been used by farmers for control of *P. hysterophorous* based on research by the University of the West Indies, Trinidad and the Ministry of Agriculture, Trinidad [5; 6]. The two most promising herbicides bromoxynil and glufosinate ammonium were applied post-emergence in solanaceous vegetable crops. Both butralin and diphenamid gave good control in the seedling stages as pre-emergence, but these are not very popular amongst farmers. There has been very good control of weeds and *P. hysterophorous* particularly in direct-seeded onions, when oxydiazon and Ioxynil + 2,4-D ester were applied pre-emergence, with no phytotoxicity.

Agricultural Extension Workers have reported for several years the inability of both glyphosate and gramoxone to control *P. hysterophorous*. This apparent resistance, coupled with the high reproductive capacity of the weed and its wide-ecological amplitude, has given rise to the increased scourge of *P. hysterophorous* in vegetable crops in the Caribbean. In other parts of the world, a similar response is obtained with respect to the resistance by both herbicides [Table 9].

Herbicide	Trade Name	Time of Application	Weed Control Efficiency Rating
Bromoxynil	Buctril	Post-Em	5
Glufosinate ammonium	Basta	Post-Em	5
Oxadiazon	Ronstar	Pre-Em	4
Ioxynil + 2,4-D ester	Actril D	Pre-Em	4
Paraquat	Gramoxone	Post-Em	0
Glyphosate	Round-up	Post-Em	0
Alachlor	Pilarzo	Post-Em	5
Dinitroaniline	Butralin	Post-Em	5
Diphenamid	Enide	Pre-Em	4
(Post-Em – post-emergent; Pre-Em – pre-emergent)			

Table 8. Herbicides used by farmers for the control of *Parthenium hysterophorous* in vegetable crops.

Herbicide	Time of Application	Weed Control Efficiency Rating	Reference
Oxyfluorfen + Quizalofop ethyl	Pre-Em	4	[32]
Atrazine + Pendimethalin	Pre-Em	4	
Pendimethalin fb 2,4-D sodium salt	Pre-Em	4	[33]
Metsulfuron methyl	Pre-Em	4	
Oxyfluorfen	Pre-Em	**3**	[34]
Glyphosate + Isoproturon	Post-Em	5	[35]
Chwastox + Buctril	Post-Em	4	[35]
Imazapyr 6.86	Post-Em	3	

Herbicide	Time of Application	Weed Control Efficiency Rating	Reference
Metsulfuron-methyl 36 g a.i. ha-1 3.93	Pre-Em	3	
Metsulfuron-methyl 4.6 g a.i. ha-1 2.59	Post-Em	3	
Atrazine 2.54	Post-Em	2	
Imazapic 240 g a.i. ha-1 2.44	Post-Em	22	
Metsulfuron-methyl 36 g a.i. ha-1 1.79	Post-Em	2	
Imazapic 1.59	Post-Em	2	
2,4-D (D.M.A. salt) + Dicamba (D.M.A. salt)	Post-Em	4	[24]
Atrazine + Dicamba	Post-Em	5	
Atrazine + 2,4-D (D.M.A. salt)	Post-Em	5	
Atrazine + 2,4-D (Na salt)	Post-Em	5	
Pretilachlor	Pre-Em	3	[33; 34]
Oxyfluorfen + 2,4-D	Pre-Em	3	
Oxadiazon	Pre-Em	4	
Thiobencarb + 2,4-D	Pre-Em	4	
Oxyfluorfen	Pre-Em	4	
Anilofos + 2,4-D	Post-Em	4	
Butachlor + 2,4-D	Post-Em	5	
Atrazine	Post-Em	33	[30; 32; 33]
Metribuzin	Post-Em	3	
Chlorimuron	Post-Em	3	
Glufosinate ammonium	Post-Em	5	
Paraquat	Post-Em	0	
Glyphosate	Post-Em	0	

Table 9. Commonly used herbicides in the control of *Parthenium* in vegetable production in other regions.

8.5. Biological control

There are no current biocontrol strategies for the management of *P. hysterophorus* reported in the Caribbean. Biocontrol of *P. hysterophorus* is reported as the most cost-effective, environmentally friendly and ecologically viable method of control. While several organisms exist locally, there is no observable damage to either seedlings or mature plants. The major fungi and insects, which are reported as potential candidates for biological control of this weed, include leaf rust fungus *Puccinia xanthii* Schwein. var. *parthenii-hysterophorae* Seier, H.C. Evans

& Á. Romero (Pucciniaceae), leaf-feeding beetle *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae) and stem-boring weevil *Listronotus setosipennis* Hustache (Coleoptera: Curculionidae) [36].

Other biocontrol agents, which have been reported to show some level of control in Ethiopia, are the stem-galling moth *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae) and the seed-feeding weevil *Smicronyx lutulentus* Dietz (Coleoptera: Curculionidae) [36; 37]. These have not yet positively been identified but experience elsewhere has demonstrated that a suite of agents is required to achieve effective biological control of *Parthenium* under different environmental conditions and in different regions.

Pathogens such as *Fusarium pallidoroseum, Puccinia melampodii* and *Oidium parthenii* have also been reported as showing good potential as biocontrol agents [38; 39]. *Alternaria alternate, Puccinia abrupt* var. partheniicola (parthenium rust), *P. xanthii* and other rusts are currently being evaluated as potential mycoherbicides for the control of *Parthenium*.

The weed is not grazed by animals or other wild life.

9. Allelopathic plant species with potential in controlling *P. hysterophorus*

There are several studies reporting the use of crude extracts, plant residues and purified compounds of allelopathic plants (crops, grasses, broadleaf weeds and trees) for controlling the germination, growth and physiology of *P. hysterophorus* [40–56]. Table 10 outlines the reported plants.

Name of Plant	Plant Part Studied	Allelochemicals Present	Suppression/Inhibitory Effect(s)	References
A. Crop plants				
Oryza sativa	Root and shoot	Momilactones A and B, phenolic acids, 5,7,4′-trihydroxy-3′,5″-dimethoxyflavone and 3-isoprophyl-5-acetoxy cyclohexene-2-one-1	Reduced germination and root/shoot growth	[40–42]
Sorghum bicolor	Root and shoot	Benzoic, p-hydroxy benzoic, vanillic, m-coumaric, p-coumaric, gallic, caffeic, ferulic and chlorogenic acids	Reduced germination and root/shoot growth	[40; 41]
Helianthus annuus	Root and leaves	Phenols and terpenoides	Reduced germination and root growth	[40; 43; 44]

Name of Plant	Plant Part Studied	Allelochemicals Present	Suppression/Inhibitory Effect(s)	References
B. Grasses				
Imperata cylindrica	Aqueous extracts of all parts, especially root and shoot extracts	Caffeic, ferulic, p-hydroxybenzoic, p-coumaric, vanillic, chlorogenic and syringic acids	Reduced germination and root/shoot growth	[45; 46]
C. Broadleaf plants				
Amaranthus spinosus *Amaranthus viridis*	Leaves		Maximum inhibition of biological activities including seed germination and multiplication	[47]
Cassia occidentalis	Shoot and root		Reduced germination, shoot-cut bioassay, seedling bioassay and chloropyll	
Cassia tora	Leaves		Reduced vegetative and reproductive growth	[48]
Cannabis sativa	Leaves		Reduced germination, biomass, protein and pigment content	[49]
Withania somnifera	Leaves and roots	Withaferin A	Reduced germination and plant growth	[50; 51]
D. Trees				
Eucalyptus citriodora	Leaves	Phenolic acids, tannins, flavonides and eucalypt oils	Reduced germination	[52; 53]
Eucalyptus globulus	Leaves	Monoterpenes (cineole, citronellol, citronellal and linalool)	Reduced germination and chlorophyll content	[54]
Azadirachta indica	Leaves	Gallic, benzoic, p-coumaric, p-hydroxybenzoic vanillic, and trans-cinamic acid	Reduced germination and dry biomass	[55]
(Adapted from [56; 57])				

Table 10. Phytotoxic effects of allelopathic plants on *Parthenium*.

10. Potential for management by utilization

There are reports of innovative uses of *P. hysterophorus.* It is documented as having insecticidal, nematicidal, fungicidal and bioherbicidal (biopesticide) and growth regulator properties [17; 58]. Furthermore, studies have shown that pre- and post-emergent applications of *P. hysterophorous* extracts at high concentrations were effective in significantly decreasing the seed germination and the growth of *Eragrostis* sp. [59]. The plant is also a rich source of nitrogen, phosphorus, potassium, calcium, magnesium and chlorophyll, which makes it suitable for composting. Reports indicate that it aids in moisture conservation, which is good for enhanced root penetration and crop growth [57; 60]. It is also used as a green manure for maize and mung bean [61].

More recently, it has been found to confer many health benefits such as a remedy for skin inflammation, rheumatic pain, diarrhoea, urinary tract infections, dysentery, malaria and neuralgia [17]. Extracts from the flowers have shown significant antitumor activity [62; 63]. It has been used as a remedy for inflammation, eczema, skin rashes, herpes, rheumatic pain, cold, heart problems and gynaecological ailments [17]. It has prospects in nanomedicine to be used in applications of eco-friendly nanoparticles in bactericidal, wound healing and other medical and electronic applications [17]. It has the potential to remove heavy metals such as nickel, cadmium, cresol and dyes from the environment, eradication of aquatic weeds such as salvinia (*Salivinia molesta* Mitchell), water lettuce (*Pistia stratiotes*) and water hyacinth (*Eichhornia crassipes*) and seed germination of lovegrass (Eragrostis) [17]. It can also be used as a substrate for commercial enzyme production [64], as additives in cattle manure for biogas production [65], as a flea repellent for dogs and as a source of potash, oxalic acids and high-quality protein (HQP) in animal feed [66; 67].

11. Conclusion

Due to its invasive capacity and allelopathicproperties, *P. hysterophorous* has the potential to disrupt the natural ecosystem and threaten the biodiversity. From an earlier survey, the authors concluded that under systems of intensive vegetable production and where the use of paraquat and glyphosate are widespread, the weed has shown the ability to survive herbicide treatments, except at the seedling stage, regardless of the season and crop or management practices [68]. In addition, biological and cultural control were insignificant in reducing *Parthenium* populations. The weed can significantly reduce crop yield and quality due to its aggressive growth habit, competitiveness and allelopathic interference. It is a difficult weed to manage, and a wide variety of methods, starting with prevention and containment, are necessary to reduce the incidence and spread of this weed. An integrated approach using cultural, physical, chemical and biological approaches are necessary for the successful management of this weed. Integrated approaches following different methods coupled with proper land management and best management practices can effectively

http://dx.doi.org/10.5772/61732

control this weed. Despite the negative impact of this weed on the biodiversity, there is potential in exploring its beneficial properties as a mechanism of management.

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Chapter 7

Evaluation of Herbicide Efficacy, Injury, and Yield in White Lupin (*Lupinus albus* L.)

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61708

Abstract

White lupin is of increasing interest in the southeastern United States (US) as a winter legume cover crop or as mid-winter forage for ruminants. White lupins are poor weed competitors during early establishment, making effective weed control necessary; however, only three herbicides are currently registered for use in lupin. An experiment was conducted at two Alabama sites in 2007 and 2008 to evaluate herbicide efficacy provided by ten preemergence (PRE) and nine postemergence (POST) herbicides as well as lupin injury and yield. Overall, PRE applied herbicides, particularly imazethapyr, linuron, and flumioxazin, caused less crop injury than POST herbicides while providing ≥ 86% control of annual bluegrass, corn spurry, heartwing sorrel, henbit, and lesser swinecress six weeks after application. Grass-active herbicides, fluazifop and sethoxydim, provided greater than 95% of annual bluegrass control without causing unrecoverable lupin damage. Imazethapyr applied POST controlled shepherd's purse (96% to 98%), cutleaf evening-primrose (81% to 96%), and wild radish (71% to 99%) without lupin injury. POST-directed spray applications of glyphosate and flumioxazin provided good weed control of corn spurry (80% to 98%) and winter vetch (71% to 95%) but caused significant crop injury due to drift. In general, grain yields were only reduced with the use of chlorimuron, diclosulam, glyphosate, and thifensulfuron. This research suggests there are several herbicides not currently registered that could be beneficial for use in US lupin production.

Keywords: Alternative nitrogen source, cover crop, weed contro

1. Introduction

Conventional agriculture depends on synthetic nitrogen (N) fertilizers and herbicides for high crop performance [1]. Alternative N sources are available in the form of leguminous crops such as *Lupinus* spp. White lupin is of major interest in the southeastern US because new cultivars exhibit differential vernalization requirements similar to wheat (*Triticum aestivum* L.) and can be utilized as mid-winter forage. White lupin has been utilized in the southeastern US as a livestock feed, for human consumption and as a winter cover crop in conservation agriculture [2, 3]. Since its introduction in the 1930s, until the 1950s the US lupin production reached over 1 million ha; however, production declined with the loss of government support, cold-weather damage to seed nurseries, and the increased availability of inorganic fertilizers [3-5].

Lupinus spp. are poor weed competitors during early establishment since canopy development is slow, facilitating light penetration and subsequent weed seed germination and yield loss due to competition. Lupin reaches maximum vegetative growth during flowering when it can successfully compete with newly emerging weeds [6]. Effective weed control is necessary to ensure lupin success under competition with weed species for water, nutrients, and light [6, 7].

Previous research has been conducted to compare the effectiveness of herbicides on weed control and potential for crop injury in lupin. A successful preemergence (PRE) herbicide treatment resulting in no crop damage is pendimethalin alone, or in combination with metribuzin [8, 9]. Pendimethalin use in white lupin provided 100% control of Russian thistle (*Salsola tragus* L.) and prostrate knotweed (*Polygonum aviculare* L.) [10]. The use of PRE applied metolachlor and alachlor, primarily in mixes with other herbicides, successfully controlled annual grasses and some broadleaf weed species greater than 90% in spring-type white lupin [11, 12]. Additionally, metolachlor, alone or mixed with linuron, did not cause white lupin injury [13].

Knott [8] found that lupin are especially sensitive to postemergent (POST) herbicides. Fluazifop, as a POST application, provided ≥98% control of wheat (*Triticum aestivum* L.), triticale (x Triticosecale Wittm ex A. Camus), and annual ryegrass (*Lolium multiflorum* Lam.) without causing injury to the lupin crop [8, 14]. POST application of imazethapyr provided good weed control but resulted in 15% to 24% crop injury and yield reduction [13]. Similarly, Penner et al. [12] found that the use of imazethapyr, as either PRE or POST, caused crop damage of 35% to 60%. Hashem et al. [15] showed that interrow weed control in narrow-leaf lupin provided by paraquat plus diquat increased yields compared to glyphosate alone, glyphosate plus metrabuzin, and glyphosate followed by paraquat plus diquat.

Currently, only three herbicides are registered for use in lupin: S-metolachlor, carfentrazone-ethyl, and glyphosate [16]. Therefore, the objective of this experiment is to investigate the use of chemical weed management practices in white lupin and evaluate their effect on weed control, crop injury, and lupin grain yield.

2. Materials and methods

Experimental treatment and design. A two-year experiment was established at two test sites on the E.V. Smith Research and Extension Center of the Alabama Agricultural Experiment Station in October 2007 and 2008, respectively. The experiment was a 2 (year) x 2 (location) x 3 (cultivar) x 4 (block) x 24 (weed control) factorial treatment arrangement. The experiment design was a randomized complete block design (r = 4) nested within each year x location x cultivar combination. The weed control factor had 20 levels: one nontreated control, ten PRE-applied herbicides, and nine POST-applied herbicides (Table 1). The two locations of the experiment were the Field Crops Unit (FCU), near Shorter, AL (32.42 N, 85.88 W) and the Plant Breeding Unit (PBU), Tallassee, AL (32.49 N, 85.89 W). At FCU, the experiment was established on a Compass soil; a coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults with a loamy sand surface structure. At PBU, the experiment was conducted on a Compass Soil: a fine-loamy, mixed, semiactive, thermic Typic Hapludults with a sandy loam surface structure. The three cultivars used in the experiment were AU Homer (a high-alkaloid, indeterminate cover crop type), AU Alpha (a low-alkaloid, indeterminate forage type), and ABL 1082 (a low-alkaloid, determinate grain type experimental cultivar).

Treatment	Class	Rate	Unit
None			
S-metolachlor + Linuron	PRE	1.12 + 1.12	kg ai ha^{-1}
Metribuzin	PRE	0.42	kg ai ha^{-1}
Linuron	PRE	1.12	kg ai ha^{-1}
S-metolachlor	PRE	1.12	kg ai ha^{-1}
Pendimethalin (0.5 X)	PRE	0.84	kg ai ha^{-1}
Pendimethalin (1 X)	PRE	1.68	kg ai ha^{-1}
Pendimethalin (2 X)	PRE	3.36	kg ai ha^{-1}
Diclosulam	PRE	0.026	kg ai ha^{-1}
Flumioxazin	PRE	0.071	kg ai ha^{-1}
Imazethapyr	PRE	0.071	kg ai ha^{-1}
Thifensulfuron (2007)	POST	0.071	kg ai ha^{-1}
Carfentrazone (2008)	PDS	46.8	g product ha^{-1}
Fluazifop	POST	0.84	kg ai ha-1
Fomesafen	POST	0.28	kg ai ha-1
2,4-DB	POST	0.28	kg ai ha-1
Chlorimuron (2007)	POST	0.052	kg ai ha-1
Clove/Cinnamon Oil (2008)	PDS	6.9	L product ha^{-1}
Glyphosate	PDS	1.12	kg ai ha-1
Sethoxydim	POST	0.28	kg ai ha-1
Flumioxazin	PDS	0.071	kg ai ha-1
Imazethapyr	POST	0.071	kg ai ha-1

Table 1. Herbicide treatments, timing, and rates for 2007 and 2008 at the Field Crops Unit and Plant Breeding Unit at E.V. Smith Research Center.

Crop management. Inoculated lupin was seeded in four-row plots with a John Deer 1700 four-row vacuum planter[1] with a row spacing of 90 cm at a depth of 1.25 cm in October 2007 and October 2008. Seeding density was 17 seeds m^{-1}. Smooth seedbeds were prepared one to two weeks prior to planting in 2007. In 2008, the cultivars were planted in raised beds prepared by a KMC four-row ripper/bedder[2] due to concerns about potential saturated soil conditions at both locations. The plot length was 7.5 m at PBU and 7.5 m and 6 m at FCU in 2007 and 2008, respectively. The PRE herbicide treatments were applied one day after planting in both years. Application of POST herbicides followed 13 (2007) to 16 (2008 due to rainfall) weeks after planting.

Ratings. Weed control ratings were recorded at both locations on a scale from 0% (no weed control) to 100% (complete weed control). The nontreated control was used to estimate the level of control in the treated plots. Two weed control ratings per treatment/plot were taken in each study year. The first rating was taken six weeks after planting and PRE application in both years. The second rating was taken 22 and 26 weeks after planting in 2007/2008 and 2008/2009, respectively.

Crop injury ratings were taken on a scale from 0 (no injury/alive) to 10 (complete injury/dead). The nontreated control was considered to have 0 crop injury. In 2007/2008, crop injury ratings were taken three weeks after planting and PRE application and 15 weeks after planting. In 2008/2009, injury ratings were taken four weeks after planting and PRE application and 18 weeks after planting. In study year 2007/2008, plots at PBU and FCU were harvested on June 17, 2008. In study year 2008/2009, plots at FCU were harvested on June 16, 2009 and at PBU on June 29, 2009 due to differences in attaining maturity. The two center rows of each plot were harvested with a 2-row/10 ft Massey Ferguson plot combine[3] to determine grain yield (kg ha^{-1}).

Statistical analysis. We used generalized linear mixed models procedures as implemented in SAS[4] PROC GLIMMIX to analyze weed control data. This tool is flexible in the analysis of data with nonnormal distribution and unbalanced designs. Violations of normality and homogeneity of variance issues are often encountered when including a nontreated control treatment or percent control data with a large range. Weed control data were modelled using a binary distribution function or arcsine transformed data. Crop injury data were modelled using arcsine transformed data and then analyzed with a normal distribution function. All treatment factors and their interactions were considered fixed effects except the block factor and its interaction with the various treatment factors. Statistical significance was declared at Dunnett's $P < 0.1$.

3. Results and discussion

Weed control. Over the course of the two-year study, 14 weed species were observed. Not all species were present in all environments; therefore, weed control is presented for only those species that appear at both sites in each year of the study. At the first rating after planting, in both years, the following PRE herbicides provided greater than 90% control of all rated weed species when compared to the nontreated included: *S*-metolachlor[5]/linuron[6] mixture, metribuzin[7], diclosulam[8], flumioxazin[9], and imazethapyr[10] (Table 2). Linuron and *S*-metolachlor alone provided greater than 90% control in most instances except for henbit (*Lamium amplexicaule* L.), which was controlled by linuron at 86%, as well as lesser swinecress [*Coronopus didymus* (L.) Sm.] and heartwing sorrel (*Rumex hastatulus* Baldw.), which were controlled by *S*-metolachlor at 86% and 88%, respectively (Table 2). The mixture of *S*-metolachlor/linuron has been used previously in lupin study, even though linuron is not labeled for use in white lupin production in the southeastern US [17, 18]. In this study, at both early weed and late weed ratings, this mixture provided greater than 70% control of all rated weed species. Pendimethalin[11] provided good early season control of all weed species at the 0.5X, 1X, and 2X rate with the exception of lesser swinecress and heartwing sorrel, which were controlled less than 50% by the 0.5X and 1X rates.

Treatment		**Annual bluegrass**	**Corn spurry**		**Heartwing sorrel**	**Henbit**		**Lesser swinecress**
Name	Class	2008	2007	2008	2007	2007	2008	2008
None	Control	5	35	4	4	22	1	3
S-metolachlor/Linuron	PRE	94	99	99	94	99	92	93
Metribuzin	PRE	96	99	96	98	97	97	96
Linuron	PRE	98	99	99	92	95	86	94
S-metolachlor	PRE	95	98	76	88	90	98	86
Pendimethalin (0.5X)	PRE	86	98	97	48	97	88	45
Pendimethalin (1X)	PRE	89	94	94	46	99	97	41
Pendimethalin (2X)	PRE	93	98	98	79	99	98	78
Diclosulam	PRE	97	99	95	98	99	98	98
Flumioxazin	PRE	97	99	99	99	98	99	99
Imazethapyr	PRE	90	98	90	97	93	99	95

[a] All means were significantly different from the control plot using the Dunnett's test with P <0.1.

Table 2. Mean weed control ratings for 2007 and 2008 six weeks after lupin planting (prior to postemergence herbicide applications) at the Plant Breeding Unit at E.V. Smith Research Center, Tallassee, AL.[a]

In 2007, the second weed rating (22 weeks after planting) conducted after POST herbicide applications revealed PRE applied herbicide weed control to be greater than nontreated controls at both FCU and PBU for each rated weed species except for cutleaf evening-primrose (*Oenothera laciniata* Hill). At PBU, pendimethalin (0.5X rate) provided only 14% weed control and at FCU, cutleaf evening-primrose control was only 23% with the 1X rate of pendimethalin (Table 3). Less than 50% control was achieved for this weed species with the 2X rate of pendimethalin as well as *S*-metolachlor. The following POST applied herbicides provided greater than 50% control of all rated weed species included: fluazifop[12], chlorimuron[13], and imazethapyr. With the exception of black medic (*Medicago lupulina* L.) and crimson clover (*Trifolium incarnatum* L.), which were controlled by less than 70% (data not shown), imazethapyr controlled all broadleaf weed species by more than 80%. Ivany and McCully [13] evaluated various herbicides for use in sweet white lupin, they also showed that imazethapyr applied PRE and POST provided good broadleaf weed control (80% to 91%). Sethoxydim[14] provided good control for all weed species except for cutleaf evening-primrose, which was less than 50% at both sites. The grass weed species, annual bluegrass (*Poa annua* L.), was successfully controlled by the POST-applied grass active herbicides sethoxydim and fluazifop which is in agreement with previous research evaluating grass control in lupin [14, 19]. Thifensulfuron[15] did not provide greater weed control than the nontreated for cutleaf evening-primrose at FCU (15%) and provided less than 50% control of this species at PBU (31%) as well as corn spurry (*Spergula arvensis* L.) at FCU (43%) (Table 3). Corn spurry control was also less than 50% for fomesafen[16] at both FCU (22%) and PBU (37%) and 2,4-DB at FCU (39%). Glyphosate[17] and flumioxazin, which were both POST-directed spray applications, provided good weed control of all rated weeds at both locations (Table 3).

Treatment		**Annual bluegrass**		**Corn spurry**		**Cutleaf evening-primrose**				**Shepherd's purse**		**Winter vetch**	
		FCU	PBU	FCU	PBU	FCU			PBU	FCU	PBU	FCU	PBU
Name	Class	Mean*	Mean*	Mean*	Mean*	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean*	Mean*	Mean*	Mean*
None	Control	0	0	0	0	2		0		3	0	6	0
S-metolachlor/ Linuron	PRE	98	97	98	99	92	<0.0001	95	<0.0001	98	99	97	97
Metribuzin	PRE	98	78	96	86	94	<0.0001	91	<0.0001	99	99	89	81
Linuron	PRE	96	90	97	99	70	<0.0001	83	<0.0001	98	99	94	72
S-metolachlor	PRE	98	93	99	99	45	0.0015	36	0.0007	97	95	96	66
Pendimethalin (0.5X)	PRE	98	58	99	99	42	0.0031	14	0.5624	97	90	95	86
Pendimethalin (1X)	PRE	98	92	99	99	23	0.1595	28	0.0089	99	96	95	61
Pendimethalin (2X)	PRE	99	82	99	99	39	0.0065	48	0.0003	99	99	98	73
Diclosulam	PRE	95	68	88	97	96	<0.0001	94	<0.0001	99	99	99	97
Flumioxazin	PRE	98	80	99	99	97	<0.0001	95	<0.0001	99	99	83	74
Imazethapyr	PRE	97	87	88	97	85	<0.0001	92	<0.0001	89	97	79	60
Thifensulfuron	POST	98	64	43	98	15	0.5624	31	0.0005	98	99	98	89
Fluazifop	POST	97	99	80	65	57	0.0001	50	<0.0001	98	95	94	57

Treatment		Annual bluegrass		Corn spurry		Cutleaf evening-primrose				Shepherd's purse		Winter vetch	
Fomesafen	POST	94	67	22	37	59	<0.0001	70	<0.0001	97	98	93	63
2,4-DB	POST	93	76	39	60	98	<0.0001	99	<0.0001	99	90	96	76
Chlorimuron	POST	99	65	93	98	98	<0.0001	98	<0.0001	99	99	99	98
Glyphosate	PDS	98	89	88	92	69	<0.0001	83	<0.0001	97	99	92	71
Sethoxydim	POST	97	96	71	84	45	0.0014	45	0.0002	97	91	93	53
Flumioxazin	PDS	95	80	98	93	93	<0.0001	88	<0.0001	98	91	95	79
Imazethapyr	POST	97	77	86	88	81	<0.0001	85	<0.0001	98	96	91	65

* Denotes means within location that are all significantly different from control using Dunnett's test with P-value <0.1.

Table 3. Mean weed control ratings 22 weeks after lupin planting in 2007 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

The second weed control rating in 2008 was conducted 26 weeks after planting at both locations. Due to excessive crop injury in 2007, the POST herbicides thifensulfuron and chlorimuron were replaced with carfentrazone[18] and a clove/cinnamon oil[19] mixture. When compared to a nontreated, PRE herbicides at both locations provided good weed control for rated weed species with the exception of shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.] and cutleaf evening-primrose. At PBU, pendimethalin at the 0.5X rate and full rate did not provide better control of shepherd's purse than the nontreated (Table 4). Similar results were seen at both PBU and FCU for all rates of pendimethalin in cutleaf evening-primrose control with 10% to 12% control with the 0.5X rate, 6% to 23% control with the 1X rate, and 8% to 18% control with the 2X rate. Control of corn spurry at both locations was also lacking for several POST herbicides including: fluazifop (6% to 7%), fomesafen (14% to 19%), 2,4-DB (5% to 6%), and sethoxydim (7% to 45%) (Table 4). Fluazifop, 2,4-DB, and sethoxydim also did not increase control of shepherd's purse compared to the nontreated at PBU with 32%, 21%, and 36% control, respectively. The clove/cinnamon oil mixture achieved poor control of shepherd's purse (29%) and cutleaf evening-primrose (14%) at PBU.

Crop injury. Two-way interactions (herbicide–cultivar and location–herbicide) were significant; therefore, injury ratings are presented by location and cultivar. Injury ratings presented here as the mean crop injury was taken after the POST herbicide applications. PRE-applied herbicides in 2007 resulted in no significant increases in crop injury in comparison to nontreated, with a few exceptions. Metribuzin caused increased white lupin injury (4.45) at FCU in cultivar AU Alpha; pendimethalin at the 2X rate resulted in increased injury (3.95) at FCU for the same cultivar (Table 5). Although metribuzin injury was not repeated in 2008 for any cultivar, past research in lupin, as well as soybean has shown variable cultivar tolerance to this herbicide [8, 20]. Diclosulam caused significant injury (6.05 to 9.94) at both locations regardless of cultivar. In 2007, POST herbicide applications, in general, caused greater crop injury than PRE herbicide applications. Thifensulfuron and chlorimuron caused significant lupin damage

Treatment		Corn spurry				Cutleaf evening-primrose		Shepherd's purse				Wild radish		Winter vetch
		FCU				PBU	FCU		PBU		PBU	FCU	PBU	FCU
Name	Class	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean*	Mean*	Mean*
None	Control	0		0		0		0		0		2	0	0
S-metolachlor/ Linuron	PRE	94	<0.0001	97	<0.0001	77	<0.0001	72	<0.0001	92	<0.0001	98	99	96
Metribuzin	PRE	74	<0.0001	85	<0.0001	73	<0.0001	81	<0.0001	93	<0.0001	91	98	67
Linuron	PRE	83	<0.0001	93	<0.0001	85	<0.0001	75	<0.0001	98	<0.0001	93	99	76
S-metolachlor	PRE	57	<0.0001	63	<0.0001	30	0.0182	12	0.1984	42	0.0651	80	94	85
Pendimethalin (0.5X)	PRE	78	<0.0001	96	<0.0001	10	0.5673	12	0.1746	3	0.9999	63	97	46
Pendimethalin (1X)	PRE	98	<0.0001	92	<0.0001	23	0.0681	6	0.6044	21	0.3890	93	96	92
Pendimethalin (2X)	PRE	91	<0.0001	96	<0.0001	18	0.1434	8	0.4548	64	0.0051	96	99	83
Diclosulam	PRE	79	<0.0001	91	<0.0001	85	<0.0001	91	<0.0001	99	<0.0001	98	99	98
Flumioxazin	PRE	94	<0.0001	98	<0.0001	94	<0.0001	95	<0.0001	98	<0.0001	96	98	90
Imazethapyr	PRE	42	0.0003	97	<0.0001	48	0.0003	96	<0.0001	85	0.0002	95	99	49
Carfentrazone	POST	23	0.0292	55	0.0001	62	<0.0001	35	0.0007	69	0.0028	74	96	70
Fluazifop	POST	7	0.6489	6	0.8047	66	<0.0001	28	0.0041	32	0.1578	43	90	82
Fomesafen	POST	14	0.1718	19	0.1242	41	0.0018	75	<0.0001	94	<0.0001	99	99	77
2,4-DB	POST	6	0.7628	5	0.9214	82	<0.0001	96	<0.0001	21	0.3932	63	98	73
Clove/ Cinnamon Oil	POST	26	0.0160	32	0.0124	58	<0.0001	14	0.1984	29	0.2074	99	99	51
Glyphosate	PDS	94	<0.0001	98	<0.0001	95	<0.0001	91	<0.0001	96	<0.0001	57	97	94
Sethoxydim	POST	7	0.6549	45	0.0010	39	0.0028	25	0.0091	36	0.1083	83	95	54
Flumioxazin	PDS	80	<0.0001	81	<0.0001	81	<0.0001	68	<0.0001	60	0.0082	72	97	80
Imazethapyr	POST	34	<0.0001	96	<0.0001	82	<0.0001	96	<0.0001	97	<0.0001	71	99	68

* Denotes means within location that are all significantly different from control using Dunnett's test with P-value <0.1.

Table 4. Mean weed control ratings 26 weeks after lupin planting in 2008 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

(9.43 to 10.00), regardless of cultivar or location; therefore, they were discontinued in 2008 (Table 5). Thifensulfuron and chlorimuron were initially included in this study since they are registered for use in soybean; however, research has shown variable phytotoxicity among soybean cultivars for both herbicides [21, 22]. Research conducted by Knott [8] suggests that sulfonylurea herbicides such as metsulfuron cause variable crop injury in white lupin, ranging from limited to severe when applied at the normal field rate. Flumioxazin, as a POST-directed spray, caused significant crop injury at each location for each cultivar (4.50 to 7.84). Significant injury resulted from the use of fomesafen at FCU regardless of cultivar; however, increased injury was not observed with this herbicide at PBU. Glyphosate also resulted in increased lupin injury at FCU for ABL 1082 (6.30) and AU Alpha (5.89) (Table 5). Glyphosate is registered for POST-directed application in lupin in the US [16]; however, herbicide drift can easily cause significant crop injury. This was the most likely cause of lupin injury in our study. Injury from POST flumioxazin applications may also be attributed to drift since PRE applications of this herbicide did not result in increased crop injury in most cases; although, in drier soil conditions, increased phytotoxicity of flumioxazin has been observed in other crops. This could pose a risk for increased lupin damage [23]. Fluazifop (0.50 to 3.81), 2,4-DB (0.06 to 0.75), sethoxydim (0.26 to 2.28), and imazethapyr (0.94 to 4.45) did not result in increased lupin injury over the nontreated (Table 5).

Crop injury in 2008 resulted in less overall lupin injury than in 2007. PRE applied herbicides did not cause significant injury in comparison to a nontreated at either location for any of the cultivars except for diclosulam (5.26 to 9.00), which caused unacceptable injury, regardless of location or cultivar (Table 6). Diclosulam, which is applied either preplant incorporated (PPI) or PRE, is registered in soybean [*Glycine max* (L.) Merr.] and peanut (*Arachis hypogaea* L.) with little injury to either crop [24, 25]. Lupin injury from PRE applications of diclosulam was significant for each cultivar included in the experiment. POST-applied herbicides did not increase crop injury over nontreated except for glyphosate (4.49 to 7.76) and fomesafen in AU Alpha at both locations (3.22 to 3.48) and in AU Homer at PBU (4.00) (Table 6). Crop injury from fomesafen was noted in both years of the study with inconsistent injury for each cultivar. In other crops, such as soybean and dry beans, previous research has reported negligible fomesafen injury regardless of cultivar [26, 27]. In this study, however, it is evident that fomesafen can produce significant injury to lupin.

Grain yield. Mean grain yields (kg ha-1) were much higher for all three cultivars in 2008 as compared to 2007 (Table 7). The grain type cultivar ABL 1082 yielded highest of the three cultivars in both years. The interaction of treatment and cultivar was statistically significant.

ABL 1082. The nontreated had a mean grain yield of 1337 kg ha^{-1} in 2007 and of 2074 kg ha^{-1} in 2008. In both years, none of the PRE herbicides, with the exception of diclosulam, reduced yield. Diclosulam caused yield losses of nearly 950 kg ha^{-1} in 2007 and 1430 kg ha^{-1} in 2008 (Table 7). Two POST-applied herbicides, thifensulfuron and chlorimuron, had no measurable yields in 2007. In 2008, glyphosate was the only POST-applied herbicide that caused significant yield losses of 1700 kg ha^{-1}.

Treatment		ABL 1082				AU Alpha		AU Homer					
		FCU	PBU	FCU	PBU	FCU	PBU						
Name	Class	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value
None	Control	1.49		0.91		0.21		1.68		0.57		1.06	
S-metolachlor/ Linuron	PRE	0.38	0.8758	2.16	0.9490	1.68	0.4758	1.22	1.0000	0.26	1.0000	0.57	1.0000
Metribuzin	PRE	1.85	1.0000	1.95	0.9891	4.45*	0.0011	1.68	1.0000	0.06	0.9795	1.22	1.0000
Linuron	PRE	0.88	1.0000	2.40	0.8482	0.75	0.9980	0.91	0.9997	0.26	1.0000	1.00	1.0000
S-metolachlor	PRE	2.05	1.0000	1.22	1.0000	1.04	0.9355	1.95	1.0000	1.68	0.9422	1.46	1.0000
Pendimethalin (0.5X)	PRE	2.32	0.9999	1.22	1.0000	0.38	1.0000	1.72	1.0000	0.26	1.0000	0.75	1.0000
Pendimethalin (1X)	PRE	1.99	1.0000	0.53	1.0000	0.57	1.0000	1.46	1.0000	1.22	0.9997	0.38	0.9970
Pendimethalin (2X)	PRE	2.88	0.9652	1.46	1.0000	3.95*	0.0042	1.22	1.0000	1.46	0.9891	2.00	0.9980
Diclosulam	PRE	9.06*	<0.0001	6.05*	0.0011	9.94*	<0.0001	4.74	0.2180	8.54*	<0.0001	6.79*	0.0002
Flumioxazin	PRE	1.56	1.0000	0.26	0.9934	2.86*	0.0555	1.00	1.0000	0.13	0.9989	0.75	1.0000
Imazethapyr	PRE	1.65	1.0000	1.46	1.0000	2.08	0.2500	1.35	1.0000	0.38	1.0000	1.68	1.0000
Thifensulfuron	POST	10.00*	<0.0001	10.00*	<0.0001	9.52*	<0.0001	9.87*	<0.0001	10.00*	<0.0001	9.43*	<0.0001
Fluazifop	POST	3.81	0.5138	1.68	0.9997	0.50	1.0000	2.62	0.9997	2.71	0.3323	1.68	1.0000
Fomesafen	POST	8.00*	<0.0001	2.40	0.8482	6.78*	<0.0001	3.36	0.8909	7.37*	<0.0001	2.71	0.8047
2,4-DB	POST	0.50	0.9631	0.75	1.0000	0.57	1.0000	0.75	0.9934	0.75	1.0000	0.06	0.6103
Chlorimuron	POST	9.94*	<0.0001	9.94*	<0.0001	9.99*	<0.0001	9.62*	<0.0001	10.00*	<0.0001	9.74*	<0.0001
Glyphosate	PDS	6.30*	0.0060	2.71	0.6636	5.89*	<0.0001	1.42	1.0000	2.91	0.2497	2.18	0.9868
Sethoxydim	POST	2.28	1.0000	3.81	0.1551	0.26	1.0000	1.22	1.0000	1.22	0.9997	0.75	1.0000
Flumioxazin	PDS	7.29*	0.0003	4.50*	0.0452	7.84*	<0.0001	3.70	0.7209	6.01*	0.0002	6.02*	0.0024
Imazethapyr	POST	4.45	0.2304	0.94	1.0000	1.06	0.9242	1.46	1.0000	1.12	1.0000	1.00	1.0000

* Denotes mean crop injury significantly different from control within location using Dunnett's P-value <0.1.

Table 5. Mean crop injury ratings 15 weeks after planting in 2007 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

http://dx.doi.org/10.5772/61708

Treatment		**AU Alpha**						**AU Homer**					
		FCU	PBU	FCU	PBU	FCU	PBU						
Name	Class	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value
None	Control	0.75		1.72		0.57		1.00		1.90		1.46	
S-metolachlor/ Linuron	PRE	1.00	1.0000	3.09	0.8164	0.57	1.0000	0.57	0.9999	1.95	1.0000	1.22	1.0000
Metribuzin	PRE	2.40	0.3071	1.72	1.0000	0.26	0.9999	0.57	0.9999	0.53	0.4054	1.00	1.0000
Linuron	PRE	0.26	0.9871	1.22	1.0000	0.06	0.8164	0.57	0.9999	0.75	0.7267	1.46	1.0000
S-metolachlor	PRE	1.88	0.7463	1.22	1.0000	1.22	0.9871	0.06	0.2778	1.95	1.0000	0.57	0.8730
Pendimethalin (0.5X)	PRE	0.53	1.0000	0.94	0.9871	0.38	1.0000	0.57	0.9999	0.06*	0.0120	1.22	1.0000
Pendimethalin (1X)	PRE	0.53	1.0000	1.72	1.0000	1.06	0.9994	0.38	0.9716	0.26	0.1031	1.00	1.0000
Pendimethalin (2X)	PRE	0.91	1.0000	2.11	1.0000	0.57	1.0000	1.00	1.0000	0.38	0.2178	1.00	1.0000
Diclosulam	PRE	8.78*	<0.0001	5.26*	0.0080	9.00*	<0.0001	9.00*	<0.0001	7.60*	<0.0001	7.26*	<0.0001
Flumioxazin	PRE	0.75	1.0000	6.28*	0.0002	0.57	1.0000	2.51	0.5138	0.38	0.2178	1.68	1.0000
Imazethapyr	PRE	0.57	1.0000	2.51	0.9986	0.26	0.9999	1.22	1.0000	1.46	1.0000	1.00	1.0000
Carfentrazone	PDS	0.94	1.0000	1.22	1.0000	1.46	0.8730	0.57	0.9999	1.12	0.9932	1.72	1.0000
Fluazifop	POST	1.72	0.8730	1.46	1.0000	1.46	0.8730	1.22	1.0000	0.75	0.7267	1.22	1.0000
Fomesafen	POST	2.66	0.1776	3.22	0.7188	3.22*	0.0155	3.48*	0.0648	2.11	1.0000	4.00*	0.0981
2,4-DB	POST	1.00	1.0000	2.40	0.9998	0.38	1.0000	0.26	0.8164	0.06*	0.0120	1.00	1.0000
Clove/ Cinnamon Oil	PDS	0.57	1.0000	2.40	0.9998	0.06	0.8164	1.00	1.0000	0.75	0.7267	1.22	1.0000
Glyphosate	PDS	6.01*	<0.0001	6.26*	0.0002	4.49*	0.0001	5.25*	0.0002	3.09	0.9334	7.76*	<0.0001
Sethoxydim	POST	1.42	0.9932	0.75	0.8730	1.00	0.9999	1.00	1.0000	0.75	0.7267	1.00	1.0000
Flumioxazin	PDS	1.22	0.9999	1.22	1.0000	0.38	1.0000	1.22	1.0000	1.72	1.0000	1.72	1.0000
Imazethapyr	POST	1.22	0.9999	0.75	0.8730	0.06	0.8164	0.38	0.9716	0.94	0.9331	1.46	1.0000

* Denotes mean crop injury significantly different from control within location using Dunnett's P-value <0.1.

Table 6. Mean crop injury ratings 18 weeks after planting in 2008 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

Treatment			ABL 1082		AU Alpha	AU Homer	ABL 1082	AU Alpha		AU Homer	
Name	Class	Mean	Dunnett's P-value	Mean*	Mean*	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value
None	Control	1337		702	555	2074		1957		1219	
S-metolachlor/ Linuron	PRE	1331	1.0000	734	877	1936	1.0000	1108	0.0011	1262	1.0000
Metribuzin	PRE	1174	0.9831	778	551	1612	0.2811	1410	0.1150	1368	0.9315
Linuron	PRE	1370	1.0000	700	729	2126	1.0000	1484	0.2526	1359	1.0000
S-metolachlor	PRE	1176	0.9855	825	671	1910	0.9998	1426	0.1384	1027	0.5331
Pendimethalin (0.5X)	PRE	1353	1.0000	664	740	1937	1.0000	1567	0.5104	1522	0.7994
Pendimethalin (1X)	PRE	1256	1.0000	767	617	2025	1.0000	1504	0.3048	1233	1.0000
Pendimethalin (2X)	PRE	1294	1.0000	719	585	1907	0.9997	1619	0.7094	1442	0.8990
Diclosulam	PRE	391	<0.0001	383	214	648	<0.0001	210	<0.0001	548	0.0667
Flumioxazin	PRE	1305	1.0000	594	674	1470	0.0565	1264	0.0159	1217	1.0000
Imazethapyr	PRE	1323	1.0000	632	630	1742	0.7320	1460	0.1984	1309	1.0000
Thifensulfuron (2007)	POST	0	<0.0001	218	177	----	----	----	----	----	----
Carfentrazone (2008)	POST	----	----	----	----	2081	1.0000	1877	1.0000	1203	1.0000
Fluazifop	POST	1094	0.6993	893	536	1889	0.9987	1827	1.0000	1573	0.7980
Fomesafen	POST	1167	0.9744	666	666	1738	0.7189	1511	0.3234	1372	0.9390
2,4-DB	POST	1216	0.9996	892	783	2180	1.0000	1321	0.0364	1580	0.7716
Chlorimuron (2007)	POST	0	<0.0001	0	143	----	----	----	----	----	----
Clove/cinnamon oil (2008)	POST	----	----	----	----	2195	1.0000	1618	0.7065	1347	1.0000
Glyphosate	PDS	971	0.1563	673	634	364	<0.0001	735	<0.0001	839	0.3234
Sethoxydim	POST	1261	1.0000	706	525	1941	1.0000	1309	0.0309	1313	1.0000
Flumioxazin	PDS	1229	0.9999	597	652	1938	1.0000	1350	0.0545	1153	1.0000
Imazethapyr	POST	1317	1.0000	557	695	2020	1.0000	1226	0.0087	1433	0.9770

* Denotes mean grain yield not significantly different from control within cultivar using Dunnett's P-value <0.1.

Table 7. Mean grain yield (kg ha^{-1}) for 2007 and 2008 at E.V. Smith Research Center, Tallassee, AL averaged across location.

AU Alpha. Mean grain yields of 702 kg ha^{-1} in 2007 and 1957 kg ha^{-1} were obtained in the nontreated (Table 7). In 2007, none of the PRE- and POST-applied herbicides reduced yield. However, the POST herbicides, thifensulfuron and chlorimuron, yielded 218 kg ha^{-1} and 0 kg ha^{-1}, respectively. In 2008, diclosulam, with a mean grain yield of 210 kg ha^{-1}, was the only PRE herbicide that reduced mean grain yield of this cultivar. Similarly, glyphosate, with a mean grain yield 735 kg ha^{-1}, was the only POST herbicide that caused significant yield reduction in 2008.

AU Homer. The nontreated control had a mean grain yield of 555 kg ha^{-1} in 2007 and 1219 kg ha^{-1} in 2008 (Table 7). None of the PRE and POST herbicide treatments significantly reduced or increased yield as compared to the control in 2007. In 2008, none of the PRE or POST herbicide applications, with the exception of PRE diclosulam (548 kg ha^{-1}), yielded lower than the nontreated control.

Experiments conducted by Payne et al. [4] in the Pacific Northwest showed a maximum white lupin yield of 2128 kg ha^{-1}, but this yield is not stable. In our study, yield within each cultivar varied greatly between years depending on the treatment. The grain-type cultivar ABL 1082 had the highest mean grain yield, followed by the forage-type cultivar AU Alpha and the cover-crop-type cultivar AU Homer. In this experiment, diclosulam, thifensulfuron, chlorimuron, and glyphosate caused major grain yield losses. AU Homer appears to be the least sensitive to herbicide-induced yield reductions, since neither thifensulfuron nor chlorimuron reduced grain yield. Ivany and McCully [13] stated that POST applications of imazethapyr caused severe crop injury and yield loss in sweet white lupin. The results of this study did not confirm their findings. Neither the PRE nor the POST imazethpyr applications caused significant crop injury or subsequent yield reduction. This could be due, in part, to the use of different cultivars than those used by Ivany and McCully [13].

In general, PRE herbicide applications included in this study, excluding diclosulam, could be used in lupin without posing a significant risk of crop injury. Previous observations by Dittman [28] agree with findings that PRE herbicides may cause less lupin injury than POST herbicide options. Certain POST herbicides, such as thifensulfuron, chlorimuron, and fomesafen, are not viable herbicide options for use in lupin. Other POST options, like fluazifop, 2,4-DB, sethoxydim, and imazethapyr, may offer additional options for weed control in lupin without increasing crop injury.

The results of this experiment show that good weed control can be achieved by using a broad spectrum of herbicides that are currently not registered for use in US lupin production such as imazethapyr, flumioxazin, and linuron. With glyphosate and *S*-metolachlor, which are registered for use in lupin in the US, good weed control in lupin is possible; however, the use of a limited number of active ingredients can potentially increase resistance development in weed species in these systems. Based on these results, it is necessary to expand the number of registered herbicides for use in US lupin production.

4. Sources of materials

[1] John Deere 1700 four-row vacuum planter, John Deere, Moline, IL.

[2] Four-row ripper/bedder, Kelley Manufacturing Co., Tifton, GA.

[3]Two-row Massey Ferguson plot combine, AGCO Corporation, Duluth, GA.

[4]Statistical Analysis Systems®, version 9.2, SAS Institute, Inc., Cary, NC.

[5] S-metolachlor, Dual Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC.

[6] Linuron, Lorox® DF, Tessenderlo Kerley, Inc., Phoenix, AZ.

[7] Metribuzin, Sencor®, Bayer CropScience, Research Triangle Park, NC.

[8] Diclosulam, Strongarm®, Dow AgroSciences, LLC, Indianapolis, IN.

[9] Flumioxazin, Valor®, Valent USA Corporation, Walnut Creek, CA.

[10] Imazethapyr, Pursuit®, BASF Corporation, Research Triangle Park, NC.

[11] Pendimethalin, Prowl® H2O, BASF Corporation, Research Triangle Park, NC.

[12] Fluazifop, Fusilade® DX, Syngenta Crop Protection, Inc., Greensboro, NC.

[13] Chlorimuron, DupontTM Classic®, E.I. duPont de Nemours & Company, Wilmington, DE.

[14] Sethoxydim, Poast Plus®, BASF Corporation, Research Triangle Park, NC.

[15] Thifensulfuron, DupontTM Harmony® SG, E.I. duPont de Nemours & Company, Wilmington, DE.

[16] Fomesafen, Reflex®, Syngenta Crop Protection, Inc., Greensboro, NC.

[17] Glyphosate, Honcho® Plus, Monsanto Company, St. Louis, MO.

[18] Carfentrazone, Aim® EC, FMC Corporation, Philadelphia, PA.

[19] Clove/cinnamon oil, Weed ZapTM, JH Biotech, Inc., Ventura, CA.

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http://dx.doi.org/10.5772/61708

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Chapter 8

The Competitive Ability of Weed Community with Selected Crucifer Oilseed Crops

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/60849

Abstract

Dedicated production of energy crops on agricultural land is expected to be a crucial source of biomass to be exploited in order to achieve the renewable energy targets in the European Union. Vegetable oils are the main source for the production of biofuel; therefore, an alternative is to use oils from non-food oilseed crops. Oilseed crops examples include rapeseed, crambe and camelina.

Most oilseed crops are considered minor crops and have received much less research attention in numerous areas, including agronomy, development of weed management strategies and determination of environmental benefits and production challenges. The use of these crops may be positive when all the benefits to the cropping system (mainly in terms of soil coverage and inhibition of weeds emergence) are considered. The strongly competitive cultivars and appropriate fertilisation are strategies used to develop appropriate integrated weed management systems. However, currently, there are few data on evaluation of oilseed competition with weed community in a semiarid climate.

We conducted one study aimed at assessing the weed community in five oilseed crops: three rapeseed species (*Brassica carinata* A. Braun., *Brassica juncea* L. and *Brassica nigra* L.), crambe (*Crambe abyssinica* Hochst. ex R.E. Fries) and *Camelina sativa* (L.) Crantz. Seed yields, yield components and plant height of each oil seed species were recorded. We evaluate these species in two irrigation levels (fully irrigated and without irrigation) and three nitrogen fertiliser doses: 0, 75 and 150 kg N ha^{-1}.

Keywords: Fertilisation, Irrigation, Drought, Weed, Yield, Brassica, Competition

1. Introduction

The crucifer oilseed crops are grown outdoors in nearly all temperate climates where there are fertile soils and adequate soil moisture. Production of these crops has increased, thanks to plant breeding advances and consumer demand. The growth and cultivation of these crops depend on many factors including the crop variety itself, the availability of light and water, the environmental temperature and the concentration of CO_2 – all of which interact in complex ways.

The majority of oilseed crops initially grow very slowly and establish a relatively reduced ground cover; they are therefore very sensitive to the presence of weeds [1]. In addition, the growth requirements of crops include abundant soil moisture, fertile soil and warm temperatures – requirements that also promote the appearance of a large number of weed species. Moreover, many weeds emerge throughout the crop cycle and can reach high infestation densities.

The characteristics of oilseed crops place them at a competitive disadvantage compared to most of the weeds that infest them: weeds grow more quickly and have a greater capacity to obtain resources from the growing environment. The damage caused by weeds competing for water, light and nutrients is well known.

The standard definition of a weed in agricultural land is an undesired plant [2-3]. Weeds cause ecological damage if they successfully colonise habitats or niches occupied by plants of agricultural interest. Weeds have characteristics that favour their dispersion and persistence, thus favouring their success in cultivated fields. These properties have been determined [3] and are summarised below:

- They can reproduce at early stages in their growth and mature rapidly.
- Some have several methods of reproduction; most use either seeds or vegetative propagation.
- They can withstand adverse environmental conditions.
- The seeds of many weeds are often the same size and shape as crop plant seeds, which facilitate their distribution.
- They germinate asynchronously over the year or over several years, allowing them to avoid adverse conditions and to emerge in successive fluxes during the crop growth cycle.
- Weeds have great capacity to compete for water, light and nutrients.
- They are found in numerous habitats.
- Many species of weeds have morphological characteristics that render them more competitive, e.g. they may show greater root development [4], be taller than the crop [5] or have a greater leaf area [6].

2. Factors involved in competition between crops and weeds

Plant species that grow at the same time are bound to enter into competition for resources such as **water**, light and nutrients, all the more so if these resources are limited. Such is the outcome when weeds infest cultivated crops, whether these are indigenous weed species that traditionally grow in the cultivated areas or invasive species from other, more distant habitats. As a consequence of competition, crop growth and/or yield can be reduced and plant morphology can even be altered [7].

When weeds compete with crops for water, they reduce the amount available to the crop, contributing towards water stress. The water deficit is a limiting factor to the production of crops, and the presence of weeds increases the water stress severity [8-9].

Light is a very important resource [10] for which crop plants and weeds compete. In the early stages of crop development, competition for light is practically null, but as the seedlings develop, they begin to shade one another. If the height of the weed is the same as that of the crop, both will be equally competitive. If the weed is smaller than the crop, the latter will be more competitive (this could be an advantage when trying to control weeds). The quantity and quality of light received are important factors affecting crop yield.

The availability of nutrients in the soil also affects the competition between weeds and crops. Soil nutrient supplies are generally limited and have to be shared by both. Those absorbed by the weeds are lost by the crop which must, in the end, reflect this deficit. In poor soils, yields improve with the application of nutrients, especially nitrogen, phosphorus and potassium, which clearly promote plant growth. However, some authors indicate that such applications benefit weeds more so than crops, increasing the farmers' negative impact [11]. In situations in which nutrient supply is limited, some weeds can absorb greater quantities of nitrogen. Some authors report that the ability to extract nutrients from the soil differs among weed species but is usually greater than that of crop plants [12-13-14].

Cultivated species, such as those of the family Brassicaceae, generally absorb great quantities of nutrients, depending on the quantity of seed fruit and dry matter they produce. This in turn is influenced by genetic and environmental variables. In the absence of other limiting factors, the absorption of nutrients and final yield are closely related. Therefore, the nitrogen fertilisation is intimately related to the yields obtained and their quality [14-15].

Mineral nutrition can be a determining factor during certain periods of the crop cycle, especially when the reproductive stage is reached. The quantity of fertilising nutrients to be applied will depend on variety, potential yield, quantities of nutrients already in the soil and growth conditions. The majority of the nutrients in fruits are usually absorbed by the plant during flowering; a period of great nitrogen, phosphorus and potassium requirement runs from the first ten days after flowering to just before seed ripening in Brassicaceae.

Nitrogen is the nutrient that most alters the chemical composition of plants. An inadequate supply to crops can cause a notable fall in production. Adequate supplementation is vital to obtain a good yield. Nitrogen may be one of the first resources for which competition occurs, and this is reflected in smaller leaf growth. Competition between weeds and crops for nutrients is not independent of interaction with other resources. Nitrates are a potential factor for competition between crops and weeds when water is not a limiting factor. Weeds can reduce the amount of nutrients available to wheat by 30–40 % [16].

Other factors that characterise the relationship between crops and weeds are weed density and the length of time of those weeds persists [5, 17]. With respect to weed density, indices of competition with the crop have been determined.

Weeds emerge in successive fluxes during the crop growth cycle. This property provides them with a very important competitive edge: they can emerge before the crop, alongside it or after it. It is known that the first species to establish itself has the best chance of dominating, so if weeds emerge before the crop, the latter is likely to suffer large losses. However, the simultaneous and even the later emergence of weed has been observed to cause severe damage to crops. Crop losses have often been related to weed emergence times and consequently to the differential growth of weeds and crops.

3. Oilseed crops as potential feedstock and biofuel production

The transport sector relies heavily on diesel fuel, the demand for which is increasing steadily. This has led to the need for alternative fuels which are technically feasible, economically competitive, environmentally acceptable and readily available. Biodiesel, which is synthesised by trans-esterification of vegetable oils or animal fats sources, is an alternative to diesel fuel because it is produced from renewable sources and involves lower emissions than petroleum diesel during manufacture. In today's society, the constant concern of high petroleum prices, environmental considerations, unstable supply and geopolitical issues are all attributable to biofuel production being one of the most controversial and popular topics on the political agenda [1]. Political factors and a number of other incentives at the state level have also attributed to the interest in biofuel production. These factors have arisen at a time of significantly low agricultural commodity prices and have led to a relatively quick expansion in the interest and production of biofuels [18].

In temperate climates, biodiesel could be obtained from sunflower, soya or others; however, crops able to grow in marginal land and with high productivity are required [19]. Several crucifer oilseed crops could be a suitable alternative due to their adaptability to temperate and semiarid climates: a strong pivoting root enables high yields even under low rainfall; they have a strong resistance to diseases and pests and the tendency for pod not to shatter under high temperatures.

Brassicaceae crops, which include canola, rape and mustard, have been used as a rotational crop with wheat and barley. Rapeseed provides an alternative for cereal-based agricultural systems, as it is broad leaved and can be grown as a break crop for a continuous run of cereals [20]. These crops are produced extensively in Europe, Canada, Asia, Australia and the United States [21]. The benefit of rotating oilseed crops with cereal grains is that they allow a wider choice of herbicide use, improving overall system weed control. The addition of oilseed crops also helps loosen hardpan and can be direct-seeded or no-till farmed, reducing soil erosion impacts and breaking disease cycles.

http://dx.doi.org/10.5772/60849

Oilseed crops contain a high oil content which makes them a good candidate for producing feedstock oils for biodiesel. Only 5–6 % of the world production of oil crops is used for seed (oilseeds) and animal feed, while about 8 % is used for food. The remaining 86 % is processed into oil [22]. Biodiesel can be produced from a wide variety of oilseed crops. In Europe, rapeseed oil is the major biodiesel feedstock. In the United States, soybeans are the dominant biodiesel feedstock.

As a result of energy supply concerns, alternative energy sources such as mass biofuel production are in high demand. Large-scale production of biofuel crops will have serious impacts on the agriculture sector in terms of quantities, prices and production locations.

4. Damages caused by weeds in oilseed crops

Herbicides are the dominant tool applied to control weeds in modern agriculture. They are highly effective in controlling most of weed species. However, they are not a complete solution to the complex challenge that weeds present [23]. Recently, public concern has been raised about the environmental pollution caused by overuse of herbicides as well as the increase in herbicide-resistant weeds. Therefore, reliable IWM (integrated weed management) strategies are required [23-24].

Dedicated production of energy crops on agricultural land is expected to be a crucial source of biomass to be exploited in order to achieve the renewable energy targets in the European Union. Vegetable oils are the main source for the production of biofuel; therefore, it is very convenient to use oils from non-food crops [25]. Oilseed crops have great potential for biofuel production and are one of the best alternatives, as, for example, rapeseed, crambe and camelina [26].

Most oilseed crops, including crambe and camelina, are considered minor crops and have received much less research attention in numerous areas, including agronomy, development of weed management strategies and determination of environmental benefits and production challenges [27]. Oilseed crop production generally is rare in the drier semiarid regions due to their poor productivity under drought conditions [28], particularly in comparison with legume crops.

Weeds typically are readily controlled in cereal crops by applying herbicides, but they can be exceptionally difficult to manage in crucifer crop production [1]. Dominant weeds, such as wild mustard (*Sinapis arvense* L.) in the rapeseed crops, can cause major yield losses. A strongly persistent seed bank, competitive growth habit and high fecundity all contribute to its nature as a dominant weed and ensure that it will be a continuing problem [29]. With wild mustard densities of 10–20 plants m^2, rapeseed yield in Ontario, Canada, was reduced by 20 to 36 %, and similar lambsquarter densities reduced by 20–25% the rapeseed yield [30].

In the field, competition for available water and light is linked to nutrient supply. In addition to yield losses, weeds can reduce oilseed crop quality even at a low density. It has been observed that seeds of rapeseed contaminated with those of wild mustard had increased linolenic and erucic acid levels in the extracted oil and glucosinolate content in the meal [31].

Increased competitive ability among cultivars has been attributed to early seedling emergence, seedling vigour, rapid root growth and rate of leaf expansion, early root and shoots biomass accumulation and canopy closure and plant height [24, 32-33]. The variation in crop competitiveness depends on crop species (intraspecific competition).

Farmers require precise information on the ability of oilseed crops to compete effectively with weeds and on integrated weed-management programs, so as to encourage their adoption.

5. A case of study: The competitive ability of weed community with selected crucifer oilseed crops

Currently, the cultivation of oilseed feedstock to make biofuel is hampered by the lack of knowledge of production practices, including questions about fertilisation and environmental conditions [34]. The use of these crops may be positive when all the benefits to the cropping system (mainly in terms of soil coverage and inhibition of weeds emergence) are considered. The strongly competitive cultivars and fertilisation are strategies used to develop appropriate integrated weed management systems. However, there are little data concerning oilseed production in semiarid climate. We conducted a study to assess the weed presence in five crucifer oilseed cultivars in response to two irrigation levels and three nitrogen doses, over two years of study.

5.1. Study area

The study was conducted at the field-testing lands of the INIA (Figure 1), La Canaleja (Alcalá de Henares, Madrid, Spain: 40º 32′N and 3º20′W; 600 m). The soil was a loamy sandy Calcic Haploxeralf [35] characterised by a lime horizon within a metre of the surface. It had a loamy sandy texture in the two surface horizons (Ap, Bt), changing to sandy with depth (CCa). The soil had 5 % total carbonate, 1 % active limestone and an average pH of 7.8 in the upper 60 cm [36]. At initiation of the experiment, the soil contained low initial organic carbon content (around 7 g kg^{-1}). Mean interannual precipitation at the site is 386 mm (mean of 20 years), 50 % of which occurring from February through June. The study was located on land that grew winter wheat (*Triticum aestivum* L.) in the preceding years.

5.2. Experimental design and treatments

The experimental design was a randomised complete block in a split-plot arrangement (Figure 2). There were 5 cultivars studied, arranged in to two whole plots by two irrigation levels: irrigation (I) and no irrigation (NI). These whole plots were divided into three subplot levels – according to nitrogen fertiliser dosage. The N fertiliser doses were 0 g N ha^{-1}, 75 kg N ha^{-1} and 150 kg N ha^{-1}. Oilseed crops cultivars were *Brassica carinata* A. Braun, *Brassica juncea* (L.), *Brassica nigra* (L.), *Crambe abyssinica* Hochst. ex. R.E. Fries and *Camelina sativa* (L.) Crantz. The five oil crops were sown at the beginning of March in 1 x 15 m2 subplots with an interrow of 0.17 m, and the seed density was 400 seeds m^2. There were four replicates of each assay, and the experiment was repeated in 2 years, 2012 and 2013.

http://dx.doi.org/10.5772/60849

Figure 1. Cultivar trials in the experimental farm "La Canaleja"

5.3. Data collection of crop yield and weed measurements

Every year during the study, plants in all subplots were harvested to determine oilseed yield (g/m^2) and yield components (plant number/m^2; silique (number/plant); silique number/m^2; seed number/silique; 1,000-seed weight (g); straw (g/m^2)).

Each year, when 50 % of the plants in the subplots were in flower, data on weed density and number of species were determined from two samples of 0.1 m^2 quadrats per subplot, for each cultivar. Weeds were harvested, and we obtained the fresh weight. Then, the weed samples were placed in a forced air oven at 80 ºC for 48 h to obtain the dry weight.

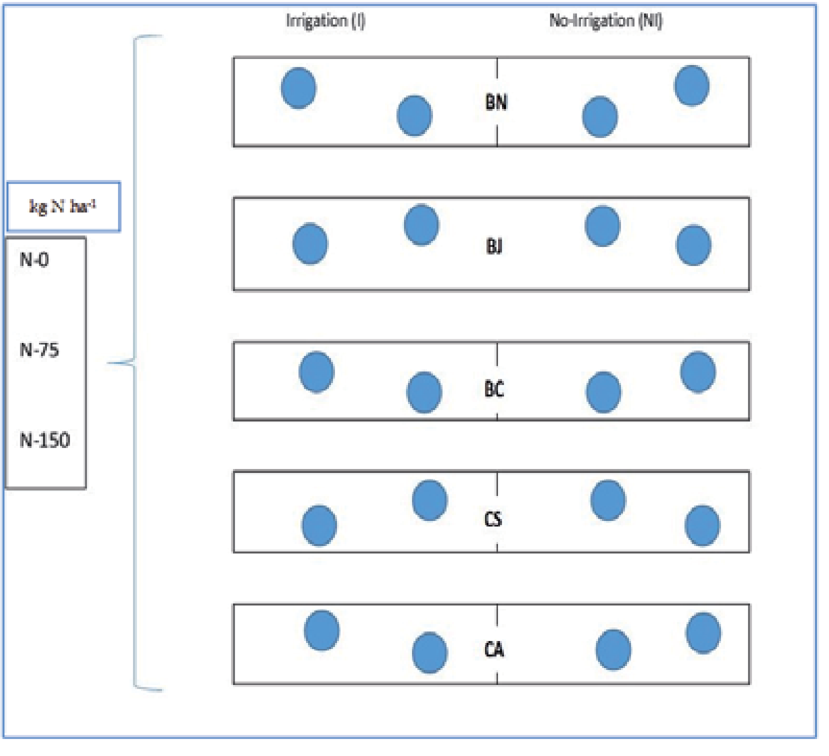

Figure 2. Weeds sampling scheme realised in each subplot **BJ**, *Brassica juncea* (L.); **BC**, *Brassica carinata* A. Braun; **BN**, *Brassica nigra* (L.); **CA**, *Crambe abyssinica* Hochst. ex. R.E. Fries; **CS**, *Camelina sativa* (L.) Crantz

5.4. Statistical analysis

Each year of study, a Proc Mixed GLM procedure was employed to compare the irrigation levels, N doses and oilseed cultivars and interactions, on seed yield components of *Brassicaceae* crops and all weed data. Means were separated by using the Tukey test at 0.05 probability level ($P<0.05$). Weed density, fresh weight and dry weight were log transformed prior to analysis to normalise residues. All data were analysed using the SAS package (SAS Institute Inc., 2003) and Statgraphics Plus 5.0 software package (Statgraphics Plus for Windows, Statpoint Technologies, Inc., USA).

6. Results and discussion

Growing season precipitation and temperature varied. In the 2012 growing season, rainfall was very low, with almost no precipitation throughout the months of March and June (77.4 mm) and high temperatures in May. In 2013, rainfall conditions were adequate for the development of crucifer oilseed crops between the months of March and June; the precipitation recorded (158 mm) was twice that of the previous year (Figure 3).

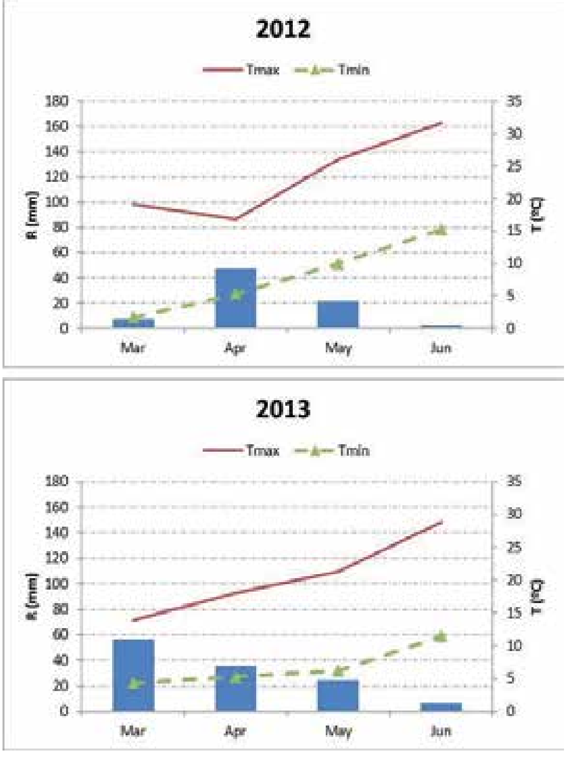

Figure 3. Monthly rainfall and maximum/minimum temperature at the study site in 2012 and 2013

Oilseed crop establishment varied by year in all cultivars of the study. In both years, the yield components of all species increased in response to irrigation (Tables 1 and 2). Our results indicate that the establishment of camelina was particularly higher than other species, evident as greater plant number per m2 and silique number per m^2 in both drought (2012) and wetter (2013) conditions.

2012													
	Trt.	Plant number /m^2		Silique number/ plant		Silique number/m^2		Seed number/ silique		1,000-Seed weight (g)		Straw (g/m^2)	
		I	NI	I	NI	I	NI	I	NI	I	NI	I	NI
BC	0	105.0	81.3	49.6	45.2	5300	3497	16.2	15.4	2.85	2.78	421.0	301.8
	75	110.0	98.8	75.3	25.2	8340	2422	16.5	11.5	2.53	2.12	716.7	294.3
	150	122.5	66.3	77.8	46.4	8770	2855	15.1	15.8	2.73	2.34	831.1	382.1
		112.5 A	**82.1 B**	**67.5 A**	**38.9 B**	**7470 A**	**2925 B**	**15.9**	**14.2**	**2.70**	**2.42**	**656.3 A**	**326.1 B**
BJ	0	268.8	212.5	47.8	15.1	12964	3188	11.2	8.8	1.83	1.62	680.7	261.8
	75	278.8	225.0	40.6	35.8	12309	7570	11.0	8.8	1.78	1.42	640.2	527.2
	150	181.3	116.3	49.5	53.4	8838	6431	10.4	9.4	1.76	1.49	540.6	413.5
		242.9	**184.6**	**45.9**	**34.8**	**11370 A**	**5729 B**	**10.9 A**	**9.0 B**	**1.79 A**	**1.51 B**	**620.5 A**	**400.8 B**
BN	0	161.3	160.0	83.0	39.7	13216	5870	8.9	7.1	1.05	0.98	619.0	272.3
	75	146.3	95.0	101.0	45.7	14448	4435	9.4	7.7	0.97	0.80	690.2	288.3
	150	140.0	97.5	83.8	79.0	10254	8194	9.1	7.3	0.97	0.79	823.2	494.0
		149.2	**117.5**	**89.2 A**	**54.8 B**	**12639 A**	**6166 B**	**9.1 A**	**7.3 B**	**1.00**	**0.86**	**710.8 A**	**351.6 B**
CS	0	287.5	283.8	70.0	47.5	20079	13377	14.1	14.4	0.85	0.83	494.6	408.7
	75	158.8	206.3	136.8	79.2	21830	14354	13.9	14.3	0.76	0.89	547.7	444.2
	150	142.5	90.0	118.3	160.4	15481	15176	14.1	11.2	0.87	0.70	516.2	449.2
		196.3	**193.3**	**108.3**	**95.7**	**19130**	**14303**	**14.0**	**13.3**	**0.83**	**0.81**	**519.5**	**434.0**
CA	0	216	200	147.6	83.4	32476	16874	1.0	1.0	5.02	4.66	241.1	185.9
	75	168	146	265.0	229.3	45156	32909	1.0	1.0	5.30	5.12	282.5	249.9
	150	158	189	225.8	164.7	36071	33043	1.0	1.0	4.83	4.85	279.2	301.3
		180	**178**	**212.8**	**159.1**	**37901**	**27609**	**1.0**	**1.0**	**5.05**	**4.87**	**267.6**	**245.7**

Table 1. Oilseed crops yield response to various irrigation levels (I, irrigation, and NI, no irrigation) and nitrogen rates (0, 75 and 150 kg N ha^{-1}), in 2012. Mean values followed by different letters indicate significant differences ($P<0.05$) according to the Tukey test. BJ, *Brassica juncea* (L.); BC, *Brassica carinata* A. Braun; BN, *Brassica nigra* (L.); CA, *Crambe abyssinica* Hochst. ex. R.E. Fries; CS, *Camelina sativa* (L.) Crantz

In 2012 (Table 1), data obtained of seed yields and yield components of *Brassica* species were significantly affected by drought conditions. Seed yield, compared to irrigated plots, decreased in different proportions in each crop: 70 % decrease for *Brassica carinata*, 65 % for *Brassica nigra*, 60 % for *Brassica juncea*, 50 % for *Camelina sativa* and 30 % for *Crambe abyssinica*. Some authors [25] reported large decreases in yield in response to drought for a range of cool-season oilseeds, including *Brassica juncea* and camelina. In this sense, cool-season crucifers are not highly tolerant of heat or drought stress, and yields typically are highly variable depending on the year [8, 37-38].

In 2013 (Table 2), data obtained regarding plant number and yield components of *Camelina sativa* and *Crambe abyssinica* were higher than Brassica species. Apparently, these species were better able to use the soil water content and thus gained a competitive advantage over the *Brassica* species. Generally, the species that were high yielding were also high yielding in the presence of weeds in wetter conditions. On the other hand, nitrogen treatments did not significantly affect seed yield of these oil crops in either year of study.

		2013											
	Trt.	Plant number/m²		Silique number/ plant		Silique number/m²		Seed number/ silique		1,000-Seed weight (g)		Straw (g/m²)	
		I	NI	I	NI	I	NI	I	NI	I	NI	I	NI
BC	0	143.8	97.5	52.7	37.3	7376	3530	16.8	17.0	2.29	2.11	598.0	293.9
	75	126.3	126.3	44.3	32.2	5445	3820	16.4	15.2	2.19	2.42	393.5	260.0
	150	102.5	96.3	58.3	36.4	5582	3299	18.2	16.4	2.16	2.17	450.2	227.9
		124.2	**106.7**	**51.7 A**	**35.3 B**	**6134 A**	**3550 B**	**17.1**	**16.2**	**2.21**	**2.23**	**480.5 A**	**260.6 B**
BJ	0	161.3	132.5	62.0	41.4	9923	5208	16.1	14.0	2.30	1.68	510.4	275.3
	75	145.0	136.3	36.5	24.6	5431	3318	13.4	13.6	1.93	1.82	258.2	154.7
	150	162.5	110.0	47.7	32.9	8176	3613	13.9	14.0	2.10	1.67	459.1	190.1
		156.3 A	**126.3 B**	**48.7 A**	**33.0 B**	**7843 A**	**4046 B**	**14.4**	**13.9**	**2.11 A**	**1.72 B**	**409.2 A**	**206.7 B**
BN	0	63.8	103.8	196.9	72.2	12633	7491	9.2	9.6	0.77	0.78	296.3	177.1
	75	117.5	98.8	86.4	55.2	10273	5454	9.1	8.5	0.74	0.70	318.2	191.8
	150	86.3	86.3	210.6	98.4	19234	8646	9.6	10.0	1.10	0.88	469.6	199.4
		89.2	**96.3**	**164.6 A**	**75.2 B**	**14047 A**	**7197 B**	**9.3**	**9.4**	**0.87**	**0.78**	**361.3 A**	**189.4 B**
CS	0	253.8	265.0	134.8	92.5	33856	23920	13.8	13.5	0.93	0.81	656.9	380.8
	75	332.5	192.5	115.9	111.0	37782	19185	13.4	13.8	0.97	0.85	823.6	449.9
	150	381.3	312.5	90.7	131.8	34584	39344	14.4	14.4	1.01	0.98	742.1	717.0
		322.5	**256.7**	**113.8**	**111.7**	**35407 A**	**27483 B**	**13.9**	**13.9**	**0.97**	**0.88**	**740.9 A**	**515.9 B**
CA	0	161.3	146.3	278.3	159.7	42800	23361	1.0	1.0	6.17	5.82	376.3	164.9
	75	237.5	235.0	245.6	174.9	54287	41198	1.0	1.0	5.88	5.41	398.2	277.7
	150	223.8	147.5	205.8	174.8	44452	25430	1.0	1.0	5.77	5.64	396.0	180.1
		207.5	**176.3**	**243.2 A**	**169.8 B**	**47180 A**	**29996 B**	**1.0**	**1.0**	**5.94**	**5.62**	**390.2 A**	**207.6 B**

Table 2. Oilseed crops yield response to various irrigation levels (I, irrigation, and NI, no irrigation) and nitrogen rates (0, 75 and 150 kg N ha^{-1}), in 2013. Mean values followed by different letters indicate significant differences (P<0.05) according to the Tukey test. BJ, *Brassica juncea* (L.); BC, *Brassica carinata* A. Braun; BN, *Brassica nigra* (L.); CA, *Crambe abyssinica* Hochst. ex. R.E. Fries; CS, *Camelina sativa* (L.) Crantz

The year had significant effects on weed community in all measured attributes. Overall, drought caused in the dry year (2012) compared to the wet year (2013), the reduction of weed density, number of species and fresh and dry weight of weed community (Table 3). In 2012, we observed in plots with no irrigation (NI) a significantly lower weed density and less species than plots with irrigation (I). The irrigation comparison results obtained the next year (2013) were not significant except for dry weight of weeds. In 2013, the high rainfall in March favoured the germination of weed species in all subplots, and all the parameters measured in weed community were higher than the drought conditions of 2012.

In 2012, increased nitrogen fertilisation rates reduced the measured parameters on weed community. Plots without fertilisation (N-0) showed a higher number of weeds, more species and higher fresh and dry weight compared to N-fertilised subplots. It seems that a reduced rate of fertilisation favours, in drought conditions, the competitive ability of some weeds and their prevalence among the growing crops. This could be attributable to presence of weeds favoured by rooting conditions, and as consequence, weed species are better soil water extractors than the oilseed crops. Due to its slow initial growth, the oilseed crop is exposed to infestation by fast weeds. However, the fertilised subplots (N-75 and N-150) in drought conditions showed that crops were better suited to use the nitrogen supplement than the weed community, and the nitrogen doses were adequate to favour the growth of crops. Also, the N-level increase could induce to break the dormancy of some weed seeds species whose seedlings could have succumbed later due to lack of adequate soil moisture.

The opposite response was obtained in the following (wetter) year of 2013; plots with no fertilisation (N-0) and reduced fertilisation (N-75) presented lower weed community parameter values than high fertilisation (N-150). Wetter conditions facilitate the growth of crops and consequently reducing the competitive ability of weed community.

Table 3 compares five selected oilseed cultivars in terms of weed density, number of species and fresh weight and dry weight of weed community in both years of study. In drought conditions, all weed parameters were significantly greater in *Brassica nigra* than the rest of oilseed cultivars. However, *Brassica carinata* was the cultivar most capable of inhibiting the development of weed community, thus freeing up physical space.

These results highlight that *Brassica nigra* cultivar are not well adapted to our continental climatic conditions, because of its slower growth, and therefore, its yield was lower than the rest of the cultivars. In all cases, the lowest weed infestation occurred in plots where the *Brassica carinata* was grown.

The natural community of weeds present in the assay is comprised by dicotyledonous weed species typical of crop fields in the area (Table 4). High April rainfall favoured early-emergence weeds, such as *Gallium aparine* L., *Lamium amplexicaule* L. and *Papaver rhoeas* L., and a general increase of humidity conditions in the plots favoured the late germination of annual species as *Fumaria officinalis* L., *Anacyclus clavatus* (Gouan) DC. and particularly two crucifer weed species *Descurainia sophia* (L.) Webb. ex Prantl. and *Diplotaxis erucoides* DC.; these species could be especially difficult to control in crucifer oilseed crops.

	2012				2013			
	Weed density	Number of species	FW ($g\ m^{-2}$)	DW ($g\ m^{-2}$)	Weed density	Number of species	FW ($g\ m^{-2}$)	DW ($g\ m^{-2}$)
Irrigation levels (I)	**	*	n.s.	n.s.	n.s.	n.s.	n.s.	*
I	60,0	2,5	191,7	40,9	218,3	4,3	450,5	80,7
NI	44,0	2,1	159,0	36,0	264,0	4,5	579,7	126,5
SEM	3,2	0,1	15,2	2,8	33,3	0,2	68,6	12,6
N doses (F)	***	***	**	***	n.s.	*	*	*
N-0	65,5	2,9	221,1	50,9	258,7	4,1	492,3	98,6
N-75	48,0	2,1	123,0	26,7	174,0	4,1	360,5	76,9
N-150	42,5	2,0	181,7	37,6	290,7	5,0	692,7	135,4
SEM	3,9	0,1	18,6	3,4	40,8	0,2	84,0	15,4
Cultivars (C)	***	**	***	***	*	n.s.	*	*
BJ	46,6	2,3	110,9	25,4	180,8	3,9	353,0	68,9
BC	39,1	1,6	99,6	23,2	206,6	4,4	326,1	71,5
BN	65,0	3,0	278,5	58,8	250,8	4,5	795,2	153,9
CA	45,8	2,0	189,3	42,5	383,7	4,5	651,1	130,4
CS	63,3	2,6	198,5	42,1	183,7	4,7	450,3	93,3
SEM	5,1	0,1	24,1	4,4	41,7	0,2	85,7	15,8
I x F	***	**	*	**	n.s.	n.s.	n.s.	n.s.
I x C	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
F x C	*	*	n.s.	*	n.s.	n.s.	n.s.	n.s.
I x F x C	**	n.s.	**	**	n.s.	n.s.	n.s.	n.s.

SEM: standard error or the mean. BJ, *Brassica juncea* (L.); BC, *Brassica carinata* A. Braun; BN, *Brassica nigra* (L.); CA, *Crambe abyssinica* Hochst. ex. R.E. Fries; CS, *Camelina sativa* (L.) Crantz

Table 3. Analysis of variance results (*, **, ***: significant at the 5, 1 and 0.1 % probability level, respectively) for irrigation levels, N doses and oilseed cultivars each year of study. Mean values for total weed density, number of species and fresh weight (FW) and dry weight (DW) parameters

Scientific name			
Amaranthus blitoides	*Datura stramonium*	*Lactuca serriola*	*Rapistrum rugosum*
Amaranthus retroflexus	*Descurainia sophia*	*Lamium amplexicaule*	*Roemeria hybrida*
Anacyclus clavatus	*Diplotaxis erucoides*	*Lavatera* spp.	*Senecio vulgaris*
Buglossoides arvensis	*Fumaria officinalis*	*Papaver hybridum*	*Sisymbrium irio*
Capsella bursa-pastoris	*Galium murale*	*Papaver rhoeas*	*Sonchus* spp.
Chenopodium album	*Heliotropium europaeum*	*Polygonum aviculare*	*Stellaria media*
Convolvulus arvensis	*Hypecoum procumbens*	*Portulaca oleracea*	*Veronica hederifolia*

Table 4. Weed community composition in the study

The annual distribution of rainfall may limit the effectiveness of the system used to control weeds, predisposing the specialisation of some species under certain crop conditions. Generally, the knowledge of the emergence process of weeds will increase the effectiveness of weed management, assuming an important qualitative advance in the integrated control of weed populations [39].

Previous researchers [40-41] have named management practices and climatic factors as the driving forces to explain weed species composition and richness in Northern and Central Europe. Thus, changes in flora may be the result, among other factors, of complex interactions between agronomic practices (choice of species and fertilisation) and environmental factors [42-43].

7. Conclusions

In summary, the interactions between irrigation, fertilisation and oilseed cultivars will affect weed density and growth. Our results support the idea that the competitiveness of different rapeseed species with weed community varies depending on the weather conditions and nitrogen fertilisation. The slow growth of certain rapeseed species and any consequential areas of bare ground could favour the spread of weeds and render its management rather difficult.

Additional adaptive management measures will be needed in the future to avoid an increased spread of weeds in oilseed crops. Bearing this in mind, our findings highlight the importance to select the adequate oilseed species in each environment. In this regard, farmers have to be given access to and choice of the most appropriate and cost-effective technologies for their particular circumstances.

Acknowledgements

We appreciate the funds received from FEDER, Plan E (BIOLUBS, CC09-068), for the realisation of this experiment. The authors express their sincere gratitude to José Silveira for his excellent technical support over the course of this study and to Charlotte Harvey for the expert help in proofreading this manuscript prior to submission for publication.

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Edited by Andrew Price, Jessica Kelton and Lina Sarunaite

Herbicides are one of the most widely used groups of pesticides worldwide for controlling weedy species in agricultural and non-crop settings. Due to the extensive use of herbicides and their value in weed management, herbicide research remains crucial for ensuring continued effective use of herbicides. Presently, a wide range of research continues to focus on improved herbicide use and weed biology. The authors of Herbicides, Agronomic Crops and Weed Biology cover multiple topics concerning current valuable herbicide research.

ISBN 978-953-51-5414-3

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