INFLUENCE OF *BRASSICA CARINATA* A. BRAUN CROPPING SYSTEMS ON WEED
POPULATION DYNAMICS AND EMERGENCE PATTERNS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To my family, for all their love and support

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LIST OF ABBREVIATIONS

AIC   Akaike's information criterion

ANOVA   Analysis of variance

DAP   Days after planting

FAWN   Florida Automated Weather Network

GDD   Growing degree days

IFAS   Institute of Food and Agricultural Sciences

LSD   Least significant difference

REG   Regression

RMSE   Root mean square error

UF   University of Florida

WFREC   West Florida Research and Education Center

Abstract of Thesis Presented to the Graduate School
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Crop rotation in the northern Florida are dominated by the cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogea* L.) in summer and with the fallow winter. Ethiopian mustard (*Brassica carinata* A. Braun) is a non-edible winter crop recently introduced in the region as an alternative source for biofuel production. In the current research, primary focus was to study the benefits associated with including *B. carinata* production as part of a diversified crop rotation on the weed population dynamics. It was hypothesized that *B. carinata* production in rotation to previous season summer crop affects weed population dynamics and emergence patterns. Therefore, the objectives of this thesis research were to 1) evaluate the influence of *B. carinata* on the population dynamics of winter [*Stellaria media* (L.) Vill., *Lamium amplexicaule* L., and *Oenothera laciniata* Hill)] and summer annual weed [(*Senna obtusifolia* (L.) Irwin & Barneby and *Amaranthus hybridus* L.] species, and 2) to evaluate the effects of previous summer crops on the emergence patterns of winter weed species and the effect of planting *B. carinata* on the emergence patterns of summer weed. The main plot was the crop history: 1) cotton; 2) peanut; or 3) non-crop summer fallow. The sub-plot was weed

management during the winter *B. carinata* growing season: 1) *B. carinata* with *S*-metolachlor; 2) *B. carinata* without *S*-metolachlor; or 3) weedy winter fallow (without *B. carinata* or *S*-metolachlor). The emergence of *L. amplexicaule* and *S. obtusifolia* were increased after cotton compared to summer fallow. *Brassica carinata* reduced the emergence of *A. hybridus* and *S. obtusifolia* compared to the winter fallow during its growing season even without *S*-metolachlor. Weed management treatments did not affect the biomass or yield of *B. carinata* in any of the experimental years highlighting its competitive ability over the studied winter weeds. Weed emergence timings were not affected by crop history or weed management treatments. Gompertz model adequately fit the winter and summer weed emergence patterns.

The results suggested that *B. carinata* can promote integrated weed management strategies for subsequent summer crops by mitigating the seed banks of summer weed species at the rotational level. In the meantime, growers could also implement weed control tools during the *B. carinata* to manage winter weeds using Growing Degree Days (GDD).

CHAPTER 1
LITERATURE REVIEW

Importance of *Brassica carinata* in Cropping Systems

Brassicas have been included as cover crop in various crop production systems for a long time. Brassica species such as *Brassica juncea* (L.) Czern. and *B. napus* have been used as cover crops (Hill et al., 2016). Likewise, *B. juncea* crop cover crop has been reported to improve root health in a subsequent cash crop, such as potatoes (*Solanum tuberosum* L.) (Boydston, 2004). Brassicaceae species produce a wide range of volatile and signaling compounds, such as glucosinolates, that play defense roles against herbivores, or are attractants for pollinators (Rohloff and Bones, 2005). Brassicas scavenge nutrient, enhance soil moisture and nutrient availability, suppress pests and nematodes, suppress weeds through smothering effects, promote pollinator health, improve soil health, and improve the farm economy (Hagos et al., 2020; Seepaul et al., 2019b).

Brassicaceae species such as Ethiopian mustard (*Brassica carinata* A. Braun) and rapeseed (*Brassica napus* L.) are also grown for oil production (Bozzini et al., 2007; Hagos et al., 2020). Camelina (*Camelina sativa* L. Crantz), *B. carinata*, and white mustard (*Sinapis alba* L.) have demonstrated potential for renewable jet fuel production (Seepaul et al., 2019a). Wide geographical adaptation, compatibility with the prevailing cropping systems, and production infrastructures are some reasons why the United States is producing industrial oilseed crops such as *C. sativa*, *B. carinata*, *B. napus*, and pennycress (*Thlaspi arvense* L.) (Cardone et al., 2003; Gesch et al., 2015).

Brassica carinata is being considered for production in the southeastern US because it can withstand the mild winter and produce higher yields compared to other

oilseed crops such as *C. sativa* and *B. napus* in this region (Gesch et al., 2015; Seepaul et al., 2019a). Considering the benefits that *B. carinata* could add to the bioeconomy of the subtropical region, this crop was introduced to the southeastern US in 2010.

Brassica carinata, also possesses important agronomic characteristics such as disease/pathologies resistance, drought resistance, low pod shattering, low bird predation, higher glucosinolates compound, and greater concentration of erucic acid than *C. sativa* and *B. napus* (Blackshaw et al., 2011; Gesch et al., 2015; Mulvaney et al., 2019; Seepaul et al., 2019a). *Brassica carinata* has a deep/extensive tap root system and shoot biomass that can improve soil quality, reduce erosion, and suppress weeds (Alcántara et al., 2009).

Row crop growers in the southeastern US are seeking options to enhance production and profitability, especially during the winter months when most of land is left unused following harvest of summer cash crops. Typically, *B. carinata*, an alternative cool-season crop is seeded in the late fall, grown throughout the winter, and harvested the following spring or early summer. *Brassica carinata* could diversify existing cropping systems and be an appropriate candidate to replace a significantly large winter fallow acreage in this region.

Integrated Weed Management

A sound integrated weed management (IWM) incorporates weed control tactics based on biological and ecological characteristics of weeds (Cléments et al., 1994) focusing on factors that contribute weed population survival and growth rather than responding to the problem after its occurrence (Buhler, 2002). An IWM is an ecological approach that combines weed population dynamics with long-term planning (rotation design, crop sequencing, no-tillage, crop residue management, and competitive crop

canopies) and reduced herbicide use for weed control while maintaining acceptable crop yields (Anderson, 2005; Swanton and Weise, 1991; Westerman et al., 2005). IWM uses knowledge about weed biology and crop growth to reduce herbicide applications for several reasons: 1) to reduce weed control cost from the application of chemicals and fuels, 2) to alleviate selection pressure on weeds and delay herbicide resistance, and 3) to reduce environmental toxicity and other ecological side effects from eliminating certain plant species from agroecosystems (Shaw, 1982). Over reliance on herbicide-based systems creates a suitable environment for development of herbicides resistant weeds, off-site herbicide movement, and weed population shifts making weed control more difficult for growers. To address these issues, there is a need to integrate economically and environmentally sound weed management approaches. Selection pressure on weed species can be alleviated through IWM strategies which incorporate rational use of resources and provide multiple weed control options. IWM in *B. carinata* has not been previously explored for the southeastern US. As herbicide-resistant weeds are have been widely spread in this region, it is equally important to minimize selection pressure and develop diverse weed management systems in alternative crops that do not rely on herbicides. Moreover, including *B. carinata* as a winter crop in an existing cropping /rotation could help diversify existing weed management systems (Buhler et. al, 2000; Owen, 2016; Shaner, 2014).

Brassica carinata and Crop Rotation

An important component of integrated weed management in annual systems is to count with a diverse crop rotation. Besides helping managing weed communities, crop rotation diversification provides opportunities to increase agriculture resilience to adverse environmental conditions (Bowles et al., 2020; Leibman and Dyck, 1993).

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Weed population dynamics in arable land are influenced by the cropping systems, environment and soil conditions, and management practices. Rotating crops with different life cycles supports weed management by disrupting weed adaptation to the specific production system (Blackshaw et al., 1994; Thomas and Dale, 1991). Research reported that winter wheat (*Triticum aestivum* L.) planted earlier in the fall increased spring competition with giant ragweed (*Ambrosia trifida* L.) strategically managing weeds for subsequent corn (*Zea mays* L.) or soybeans [*Glycine max* (L.) Merr.] (Goplen et al., 2016). Challenges were reported for the control of winter weeds within the sugar beet [*Beta vulgaris* (a winter biofuel crop)] planting and harvesting period in the southeastern US coastal plain where the temperature is high (Johnson et al., 2018). Rotation between cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) is common for row-crop production in the southeastern US. It would be beneficial, if winter grown *B. carinata* could be integrated into the system, without compromising summer cash crops (Katsvairo et al., 2006), yet providing weed management benefits in the long run (Hill et al., 2016).

Summer and Winter Weeds in Agronomic Row Crops

In agronomic crop production, weeds are a constant problem because of their dynamic nature. There are multiple monocotyledons and dicotyledonous weed species which are problematic in cotton, peanut, and other summer crops. Researchers reported that summer annual weeds such as *S. obtusifolia* and *A. hybridus* caused significand yield reductions in agronomic crops such as corn, soyabean, and cotton (Buchanan and Burns, 1971; Moolani et al., 1964; Thurlow and Buchanan, 1972). Weed surveys in Georgia reported *S. obtusifolia* and *Amaranthus* species among the most troublesome weeds in cotton and peanut fields (Webster and Macdonald, 2001).

Senna obtusifolia is a large-seeded weed with hard seed cover, physical dormancy, which favor persistence in the soil seed bank (Isaacs et al., 1989; Northsworthy and Oliveira, 2006). *Amaranthus hybridus* has a small seed, with physiological dormancy, and that exhibits high levels of mortality in the seed bank (Baskin and Baskin, 2004; Gallagher and Cardina, 1998). Evolution of herbicide resistant weed biotypes along with the alteration in weed management systems could increase the concerns towards *Amaranthus* species throughout the US (Webster and Macdonald, 2001).

Lamium amplexicaule has been observed in winter wheat production fields in many parts of the US (Clewis et al., 2007; Conley and Bradley, 2005). *Oenothera laciniata* and *L. amplexicaule* are in the top four most troublesome winter annual weeds in small grains and cool season crops in the southeastern US cropping systems (Webster and Macdonald, 2001; Webster, 2012). These weed species usually germinate in the fall or spring and complete their life cycle before the summer (Webster and Macdonald, 2001; Webster, 2014).

Likewise, *S. media* is also a common winter weed in most of the agricultural production systems in Florida, which emerges during fall, winter, and early spring (Khamare et al., 2019).

Winter weed species having different nature can interfere with short season winter crops in different ways. *Stellaria media* can interference with autumn planted spring cabbage in cool and wet conditions while having greater overwintering effects compared to spring emerging plants (Lawson, 1972). In one field experiments, *S. media* was illustrated as an effective competitor with winter planted barley (*Hordeum vulgare*

L.) whereas other researchers highlighted the smothering of *S. media* in spring by the winter planted rye (*Secale cereale* L.) (Fogelfors, 1977; Sobey, 1981).

Importance of Weed Emergence Timings and Patterns

In addition to the carefully designed crop rotations and cultural practices, timely action of deliberate weed control method is an important part of IWM system (Neve et al., 2011). For the successful implementation of IWM strategies, it is necessary to identify the environmental factors that influence weed emergence (Deen et al., 2001). Soil temperature and moisture are among the most important abiotic factors responsible for determining weed seedling emergence intensity and timing (Calado et al., 2009; Hartzler et al., 1999). The differences in emergence timing also rely on location and cultural practices (Forcella et al., 1992). Modeling weed emergence with thermal time or Growing Degree Days (GDD) is one way that weed control has been timed (Ball et al., 1995). Thermal time models can account for variation in environmental conditions across locations or between years to help develop effective weed management strategy in cropping systems (Hill et al., 2014). Emergence timing of the winter weeds in relation to *B. carinata* would suggest the optimum time to adopt the weed management practices.

Soil Seed Bank Management

Soil seed bank is the most important source of annual weeds emergence in agricultural fields (Cavers, 1995). Since crop rotation and weed control practices affect the composition and density of weed seed banks, the weed density in the soil is strongly influenced by the previous crop (Buhler et al., 1997). After dispersal from the mother plant, weed seeds remain dormant in the soil for subsequent crop seasons. Therefore, one of the keys to long term weed management is soil seed bank depletion (Sebastian

et al., 2017). There are several ways the seed banks can be depleted. Weed density declined when a monoculture was replaced with a crop rotation (Swanton and Weise, 1991). Diverse crop rotations provide a suitable habitat for seed predators that reduce the number of weed seeds on the soil surface. The use of crop rotation also promotes weed seed bank depletion through weed seed decay and has the potential to manage herbicide resistant weeds in the long run (Chee-Sanford et al., 2006; Goplen et al., 2017; Schreiber, 1992). Reductions in overall weed seed banks also depend on crop sequence because the transition between crops determine the rate of change in weed populations as well as species composition (Leon et al., 2015; Leon and Wright, 2018; Smith and Gross, 2006; Teasdale et al., 2004). Furthermore, variation in crop sequence creates an unfavorable environment for weed species potentially decreasing their population growth rate (Westerman et al., 2005). Weed seed banks can be helpful to study weed population dynamics; information that is important for the development of integrated weed management strategies (Koocheki et al., 2009).

Fitting *B. carinata* into existing crop rotations will not only provide growers the option of biofuel production but also could assist in managing weeds. However, *B. carinata* is a relatively new crop in the region, and there is a need to investigate rotations that are economically and agronomically feasible. Works have been performed to evaluate basic agronomic practices not limited to planting strategies, fertilization requirements, and identification of suitable genotypes adapted to the southeastern US (Kumar et al., 2020; Mulvaney et al., 2019; Seepaul et al., 2019). Regarding weed management, research was conducted to evaluate safe herbicides for weed control in *B. carinata* (Leon et al., 2017). Although crop rotation is known to be an effective

strategy for weed control, no research has been conducted to study how integrating winter *B. carinata* production in a diversified crop rotation might affect winter and summer weed population dynamics. In addition, there is no information related to previous season summer crops effect on winter weed emergence patterns and the production of *B. carinata* on summer annual weed emergence patterns (Madejón et al., 2001).

In the present research, we hypothesized that 1) prior season summer cash crops reduce weed pressure during *B. carinata* production; 2) *B. carinata* reduces populations of winter weed species during its growing season; 3) *B. carinata* lowers weed populations for the subsequent summer cash crops; and 4) previous season crop history and weed management treatments affect the emergence patterns of winter and summer annual weed species in *B. carinata*.

Therefore, the main objectives of this research were 1) to evaluate the effect of *B. carinata* on winter and summer weed population dynamics into the southeastern US crop rotation systems; 2) to assess the effect of previous summer crops on the emergence of winter weed species; and 3) to evaluate the effect of planting *B. carinata* on the emergence patterns of summer weed species.

GROWING WINTER *BRASSICA CARINATA* AS PART OF A DIVERSIFIED CROP
ROTATION FOR INTEGRATED WEED MANAGEMENT

Summary

Brassica carinata A. Braun is a non-edible, oilseed winter crop for biofuel

production, that can diversify crop rotations and improve integrated weed management.

The research objective was to evaluate the influence of *B. carinata* on weed population

dynamics in the southeastern US cropping systems. *Brassica carinata* was grown after

cotton (*Gossypium hirsutum* L.), peanut (*Arachis hypogea* L.), or a clean summer fallow,

and winter weed pressure was modified with or without *S*-metolachlor. Emergence of

Lamium amplexicaule L. increased at least 40% after cotton or peanut in 2018-2019

and 50% after cotton in 2019-2020 compared to summer fallow. *Stellaria media* (L.) Vill.

emergence was increased over three-fold after peanut or cotton in 2019-2020. *Senna*

obtusifolia (L.) H.S. Irwin & Barneby emergence after cotton was increased at least 43%

during both experimental years, while *Amaranthus hybridus* L. emergence was

increased over 50% after peanut in 2019-2020 compared to summer fallow. Even

without *S*-metolachlor, *B. carinata* reduced *A. hybridus* (>27%) and *S. obtusifolia*

(>25%) emergence compared to weedy winter fallow. After *B. carinata* harvest, *A.*

hybridus emergence was reduced >40% with or without *S*-metolachlor compared to

winter fallow in 2018-2019. Overall, *B. carinata* biomass was highest after peanut for

both seasons. *Brassica carinata* seed yield did not differ among crop history treatments

in the first season, whereas in 2019-2020, yield was higher after peanut (2,417 kg ha^{-1})

or fallow (2,520 kg ha^{-1}) compared to cotton (1,710 kg ha^{-1}). Weed management

treatments were not different for *B. carinata* biomass or yield in any year. The results

indicate that *B. carinata* can enhance integrated weed management strategies at the

rotational level for summer crops by reducing seed banks of summer weed species, besides its potential as a winter biofuel crop for the southeastern USA.

Introduction

Brassica carinata A. Braun is a semi-wild species native to Ethiopia, that originated from natural crosses between *Brassica oleracea* L. and *Brassica nigra* L. (Bozzini et al., 2007). It has been recently introduced as a non-edible winter biofuel crop in the southeastern USA (Seepaul et al., 2019a). Since this is a new crop to the region, there is limited agronomic information, which is key for grower adoption. For this reason, research efforts have been made to determine fertilization requirements, and planting arrangements and densities (Mulvaney et al., 2019; Seepaul et al., 2019b). Furthermore, research has been conducted to identify herbicides that could be both safe and effective for weed control in *B. carinata* (Leon et al., 2017). However, no research has been conducted to determine how *B. carinata* might affect weed populations as part of a diversified crop rotation.

In annual cropping systems, the rotation of crops over time has been an important strategy for water, soil, pest, and production cost management. Additionally, diversification of crops and weed control tools make it more difficult for a given weed species to become dominant (Davis et al., 2012; Leibman and Dyck, 1993). The inclusion of a rotational crop that can suppress weed growth by effectively limiting access to essential resources such as light, soil moisture, and nutrients is a key component of integrated and sustainable weed management strategies. Farmers can diversify crops in more intensive rotations for mitigating the weed problems related to monoculture cropping systems. Rotating crops with different life cycles assists weed management by disrupting weed associations to specific environmental or agricultural

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conditions (Blackshaw et al., 1994; Thomas and Dale, 1991). Furthermore, rotation design, particularly crop sequence, plays a major role in the success of crop rotations to suppress weed populations (Anderson, 2005; Westerman et al., 2005). Likewise, reductions in overall weed seed banks depend on the crop sequence (Smith and Gross, 2006; Teasdale et al., 2004). This is because crop phase determines the rate of change in weed populations as well as the species composition of the seed bank (Leon et al., 2015; Leon and Wright, 2018).

In the southeast US, rotations between cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) are common for row-crop production (Katsvairo et al., 2006). Considering that *B. carinata* introduction to the southeastern US cropping systems could influence weed communities in the existing crop rotation, it is critical to determine what changes growers should expect. For example, if growing *B. carinata* during the winter exacerbates weed problems in the summer cash crops then growers might not adopt this new bioenergy crop. Conversely, if incorporating *B. carinata* assists in solving or mitigating weed pressure in the summer cash crops, while fulfilling the oil production goal, this could increase adoption, and favor the development of robust and sustainable cropping systems for managing weed problems.

Farming intensification could also have undesirable ecological impacts such as reduced biodiversity. While in most cases, in cotton-peanut rotations growers maintain a weedy fallow or a cover crop with minimal to no weed control during the winter, growing a biofuel crop during this time of the year might decrease the number of plant species that provide habitat for beneficial organisms in the field. This is particularly likely if the biofuel crop requires intensive weed control throughout the entire growing season

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(Jose-Maria et al., 2010; Petit et al., 2015). If *B. carinata* has enough weed suppression potential to require minimal control of local winter weed species, farmers might be able to maximize yield while minimizing reductions in the plant diversity of the system.

In the present research, we studied how summer crops influence winter weed pressure during winter *B. carinata* production, as well as how this crop affects summer weed emergence. We hypothesized that 1) summer cash crops decrease weed pressure for *B. carinata*; 2) *B. carinata* reduces winter weed population during its growing/production season; and 3) *B. carinata* decreases weed populations for following summer crops. Therefore, the main objective of this research was to evaluate the effect of introduction of *B. carinata* into southeastern US crop rotation systems on winter and summer weed population dynamics.

Materials and Methods

Experimental Design

Field experiments were conducted from May 2018 to September 2019 and May 2019 to August 2020 at the West Florida Research and Education Center of the University of Florida (UF-WFREC), Jay, FL (30˚46'37" N 87˚8'20" W, 64 masl). For the 2018-2019 site, the soil was a Dothan fine sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with a pH of 6.3 and Orangeburg sandy loam (fine-loamy, kaolinitic, thermic Typic Kandiudults) mosaic with a pH of 6.0. At the 2019-2020 site, the soil was a mosaic of Orangeburg sandy loam (fine-loamy, kaolinitic, thermic Typic Kandiudults) with a pH of 6.0 and Tifton sandy loam (fine-loamy, kaolinitic, thermic Plinthic Kandiudults) with a pH of 5.8. Weather data were collected from an automated weather station located within 1 km of the research sites.

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The experiment was a randomized complete block design arranged as a split-plot with seven and eight replications in the 2018-2019 and 2019-2020 seasons, respectively. The main plot was the crop during the previous summer growing season (i.e., crop history): 1) cotton (DP 1646); 2) peanut (Georgia 06G); and 3) non-crop summer fallow. The sub-plot was weed management during the winter *B. carinata* growing season: 1) *B. carinata* (Avanza 641) with *S*-metolachlor (1,420 g a.i. ha^{-1}, Syngenta Crop Protection, Greensboro, NC, USA) applied preemergence (PRE); 2) *B. carinata* without *S*-metolachlor; and 3) weedy winter fallow (without *B. carinata* or *S*-metolachlor). These treatments were intended to compare winter weed populations with and without *B. carinata*, and how the performance of this crop is affected by low weed pressure i.e. environment created with the *S*-metolachlor application, compared with a high weed pressure in the absence of this herbicide.

Main plots were 21 m wide by 11 m long, and subplots were 7 m wide by 11 m long. For the 2018-2019 and 2019-2020 season, cotton and peanuts were planted during early May. The fertilization was done to provide a total of 101 kg ha^{-1} of nitrogen (N), 106 kg ha^{-1} of phosphorous (P), 100 kg ha^{-1} of potash (K), and 37 kg ha^{-1} of sulfur (S) for cotton. Likewise, a total of 78 kg ha^{-1} of P, 56 kg ha^{-1} of K, and 33 kg ha^{-1} of S was applied to peanut. The agronomic management and cultural practices for cotton and peanut followed the local recommendations (Wright et al., 2016; Wright et al., 2017). Preemergence and postemergence herbicides were applied to control weeds following local recommendations for cotton (Ferrell et al., 2020a) and peanut (Ferrell et al., 2020b) production. In the meantime, summer fallow was kept weed-free throughout the crop growing season.

Conventional tillage was implemented for the entire *B. carinata* research site. After cotton and peanut harvest, fields were disked twice and roto-tilled prior to *B. carinata* planting. *Senna obtusifolia* (L.) Irwin & Barneby seeds were collected from natural populations at the UF/IFAS-WFREC in 2018-2019 and obtained from Azlin Seed Service (Leland, MS) for the 2019-2020 season. *Amaranthus hybridus* L. seeds were obtained from Azlin Seed Service during both years. Prior to planting *B. carinata*, three 1-m^2 quadrats were randomly placed within each subplot. In first quadrat, *S. obtusifolia* seeds were spread at 2,000 seeds m^{-2} in November 2018 and 3,500 seeds m^{-2} in November 2019. Likewise, *A. hybridus* seeds were spread at 25,000 seeds m^{-2} for both years in the second quadrat, while the last quadrat was left for monitoring emergence of the local seed bank of winter weeds. The plots were lightly cultivated to incorporate *S. obtusifolia* and *A. hybridus* seeds in the soil. *Senna obtusifolia* and *A. hybridus* were chosen to represent summer weed species with large seeds with hard seed coats and small seeds with soft seed coats, respectively.

Brassica carinata seeds were planted at 6 kg ha^{-1} at 36 cm row spacing using a 4-meter grain-drill planter (Great Plains 1206 NT, Salina, KS) in all the plots except winter fallow (Seepaul et al., 2016). *Brassica carinata* was planted on February 4, 2019 in first year and on November 18, 2019 in second year. In 2019, although earlier planting was planned, heavy and frequent rainfall events delayed *B. carinata* planting until February (Table 1). *S*-metolachlor was applied 1-day after planting *B. carinata* with a tractor mounted sprayer using XR 11002 nozzles (TeeJet Technologies, Glendale Heights, IL) to deliver 187 L ha-1. Liming and fertilization were done according to soil tests and recommendations for canola except for N, which was applied at 22 kg ha^{-1}

immediately after planting and an additional 68 kg ha-1 was applied during early bolting. Lambda-cyhalothrin (Winfield, USA) was applied at 18 g a.i. ha-1 twice during the 2018-2019 season for aphid (Aphidoidea) and armyworm (*Spodoptera frugiperda*) control. To control armyworm (*Spodoptera frugiperda*), zeta-cypermethrin (FMC Corporation, Philadelphia, PA, USA) was applied at 28 g a.i. ha-1 once during 2019-2020 season. Prothioconazole (Bayer CropScience, NC, USA) was applied at 165 g a.i. ha^{-1} twice during 2019-2020 season for controlling Sclerotinia Stem Rot (*Sclerotinia sclerotiorum*).

Data Collection and Analysis

After planting *B. carinata* winter weed seedlings were counted in the designated 1-m^2 quadrat and removed at weekly intervals during the *B. carinata* growing season. Winter weed species included *L. amplexicaule*, *S. media*, and *O. laciniata*. Similarly, *S. obtusifolia* and *A. hybridus* seedling emergence was collected from the respective 1-m^2 quadrat on a weekly interval during *B. carinata* growing season and the subsequent summer season after the *B. carinata* harvest.

Aboveground *B. carinata* biomass was hand-harvested at maturity from a randomly assigned 1-m^2 area within the sub-plot on June 4, 2019 and May 13, 2020. Harvested *B. carinata* samples were air-dried at 65 C to determine dry biomass weight. The dry samples were hand threshed, and seed yield was recorded by adjusting at 8% moisture content.

After harvesting *B. carinata*, the field was mowed and glyphosate (Roundup PowerMax, Bayer CropSciences, USA) was applied at 1,542 g a.e. ha^{-1} to eliminate the remaining weeds. The field was strip-tilled once, and a 1-m^2 sampling area was marked in each sub-plot to track summer weeds emergence after *B. carinata* harvest. *Senna obtusifolia* and *A. hybridus* seedlings were counted and removed every week

Seedling emergence for winter weeds was converted to cumulative emergence up to *B. carinata* harvest. Similarly, the cumulative seedling emergence for summer weed species was calculated until *B. carinata* harvest and after the *B. carinata* harvest. Data were analyzed with ANOVA using the PROC GLIMMIX procedure in SAS (Statistical Analysis Systems, version 9.4, SAS Institute Inc., Cary, NC). For the initial analysis, year, crop history, weed management, and their interactions were considered as fixed effects, whereas block and its interaction with year were considered as random effect. Since year was significant, the data were analyzed separately by year. Crop history, weed management, and their interactions were considered as fixed effects, whereas blocks were considered random effects. Means were separated using Fisher's Least Significant Difference (LSD) test at $\alpha = 0.05$.

Results and Discussion

Effect of Crop History on Weed Emergence During *Brassica carinata* Production

Lamium amplexicaule emergence was influenced by crop history in 2018-2019 and 2019-2020 ($P < 0.05$) (Table 2-2). Cotton increased *L. amplexicaule* emergence 40% and 50% compared to summer fallow in 2018-2019 and 2019-2020, respectively (Figure 2-1). Although peanut increased *L. amplexicaule* emergence over 40% compared to summer fallow in 2019-2020, no response to peanut was observed on the emergence in the previous season.

Stellaria media emergence was only affected by the previous crop in 2019-2020, increasing three-fold after peanut and four-fold after cotton compared to summer fallow (Figure 2-1). Unlike the other two winter weed species, crop history did not affect *O. laciniata* emergence (Figure 2-1; Table 2-2).

Despite being considered a summer annual weed species, *A. hybridus* emergence was observed during the *B. carinata* growing season from late-February to mid-June and late- November to mid-May in 2018-2019 and 2019-2020 seasons, respectively. In 2018-2019, *A. hybridus* emergence was not affected by the previous crop (Figure 2-2). Conversely, in 2019-2020, *A. hybridus* emergence after peanut increased over 50% compared to summer fallow (Figure 2-2).

In both years, crop history had a significant effect on *S. obtusifolia* emergence ($0.001 \leq P \leq 0.02$; Table 2-2). Interestingly, when cotton was grown the previous season, *S. obtusifolia* emergence during the *B. carinata* growing season was approximately 43% higher compared to the field left fallow before *B. carinata* planting (Figure 2-2).

After *B. carinata* harvest, *S. obtusifolia* emergence was at least 23% higher after peanut compared to the non-crop summer fallow in 2018-2019 (Figure 2-2). However, crop history had no effect on *A. hybridus* emergence in any of the study year.

Crop rotations are important from a weed management perspective. Depending on the specific crops used and their durations, crop rotations possess the potential of reducing weed population densities even when herbicides are not applied (Blackshaw et al., 1994; Liebman and Dyck, 1993; Schreiber, 1992). In this study, *B. carinata* grown after cotton resulted in more *L. amplexicaule* emergence in both years and *S. media* emergence in 2019-2020 season. Positive responses from cotton was detected compared to the summer fallow for *S. obtusifolia* emergence, a summer annual weed species (Figure 2-2). High levels of soil N have been attributed for promoting weed emergence (Blackshaw et al., 2003; Hans and Johnson, 2002; Qasem, 1992;

Supasilapa et al., 1992). This might explain why *L. amplexicaule*, *S. media*, and *S. obtusifolia* emergence were favored after cotton in this experiment (Figure 2-1; 2-2). Common lambsquarters (*Chenopodium album* L.) seed germination was greater after receiving 280 kg ha-1 of ammonium nitrate compared to no nitrogen application (Fawcett and Slife, 1978). This suggests that higher nitrogen content in soil can enhance dormancy release and promote seed emergence. Thus, the results for higher winter weed emergence after cotton in this study could likely be associated with the greater nitrate concentration.

Effect of Weed Management During *Brassica carinata* on Weed Emergence

S-metolachlor applied at planting consistently reduced *L. amplexicaule* population approximately 80% in both years compared to *B. carinata* plots without the herbicide (Table 2-2; Figure 2-3). A similar result was observed in 2018-2019 for *S. media*, but no reduction in the emergence of this weed was observed in 2019-2020.

Oenothera laciniata was less susceptible to *S*-metolachlor than *L. amplexicaule* and *S. media.* The only reduction in *O. laciniata* emergence was observed in 2018-2019 after *S*-metolachlor application and was approximately 46% less compared to the *B. carinata* treatment without herbicide (Figure 2-3).

In the case of summer weed emergence during the *B. carinata* growing season, in 2018-2019, only *A. hybridus* emergence was reduced 40 to 50% when *S*-metolachlor was applied compared to the herbicide-free *B. carinata* and the fallow plots (Figure 2-4). Conversely, in 2019-2020, although the emergence of summer weeds was less than in 2018-2019, there was a clear trend in which emergence of both species was reduced as a result of preemergence *S*-metolachlor applications with *B. carinata* (P < 0.0001; Table 2-2). Thus, *S. obtusifolia* and *A. hybridus* populations were reduced in *B. carinata* with

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S-metolachlor by 36 and 89%, respectively, compared to a winter fallow (Figure 2-4).

Brassica carinata reduced *A. hybridus* emergence by more than 27% even in the

absence of *S*-metolachlor (Figure 2-4). Likewise, *S. obtusifolia* population was reduced

at least 25% in *B. carinata* without *S*-metolachlor compared to the winter fallow (Figure

2-4). Considering all species studied, the application of *S*-metolachlor reduced weed

pressure and the risk of interference with *B. carinata*.

After harvesting *B. carinata, A. hybridus* emergence was reduced by >40% with

or without *S*-metolachlor compared to the winter fallow in 2018-2019 while the weed

management treatments had no effect during the second season (Figure 2-4). *Senna*

obtusifolia emergence was not affected by the weed management treatments in both

seasons.

Brassica carinata did not reduce the winter weed species density compared to

winter fallow (Figure 2-3). Conversely, *S*-metolachlor, a safe preemergence herbicide in

B. carinata (Leon et al., 2017), successfully reduced weed pressure, allowing us to

evaluate weed interference of *B. carinata* by comparing with or without herbicide

application.

Considering that *B. carinata* will likely be (at least initially) a secondary crop in

the current cotton-peanut rotations in the southeastern US, it is critical to minimize

production costs and inputs. Even though winter weed populations with *S*-metolachlor

were reduced (Figure 2-3), *B. carinata* seed yield did not differ without this herbicide

and with a much higher weed density (Table 2-3). This is likely due to the canopy

structure of *B. carinata*, which is much taller (i.e., over 1.2 m; Seepaul et al., 2019b),

than the canopy of early emerging winter weeds such as *L. amplexicaule* and *S. media*

(i.e., less than 0.35 m; Bryson and DeFelice, 2009). Likewise, the *B. carinata* canopy is fully closed by the time *S. obtusifolia* and *A. hybridus* emergence started, favoring weed suppression, and preventing yield reduction. High weed suppressive potential has been reported for other Brassicaceae crops (Al-Khatib et al., 1997; Boydston and Hang, 1995). For example, *Brassica napus* L. suppressed the growth of *Capsella bursa-pastoris* (L.) Medik., *Setaria viridis* (L.) P.Beauv. and *Bassia scoparia* (L.) A.J.Scott by 76, 25, and 25%, respectively (Al-Khatib et al., 1997). By the time *B. carinata* was harvested, over half of the summer annual weed species populations had emerged but died (Figure 2-2; 2-4). In a traditional year with early planted summer crops, many of the *S. obtusifolia* and *A. hybridus* seedlings that were eliminated during the *B. carinata* season would likely have been present in the summer crops.

Effect of Crop History and Weed Management on *Brassica carinata* Biomass and Yield

In general, no clear trend was observed on *B. carinata* biomass production in response to crop history. For example, in 2018-2019, *B. carinata* biomass was higher when grown after peanut. (9,466 kg ha^{-1}) compared to summer fallow (7,233 kg ha^{-1}; Figure 2-5), but it was not different from cotton. In 2019-2020, *B. carinata* biomass was similar following peanut (7,647 kg ha^{-1}) and fallow (7,875 kg ha^{-1}), but lower than cotton (6,058 kg ha^{-1}; Figure 5). *Brassica carinata* seed yields were similar for all crop history treatments in 2018-2019 (Figure 2-5; Table 2-3), whereas seed yield was higher after peanut (2,417 kg ha^{-1}) and fallow (2,520 kg ha^{-1}) compared to cotton (1,710 kg ha^{-1}; Figure 2-5) in 2019-2020. Interestingly, weed management treatments did not affect *B. carinata* biomass or yield in any of the experimental years ($0.064 < P < 0.52$; Table 2-3).

Weed management treatments had no effect on *B. carinata* yield and biomass for both years (Table 2-3). It was reported that maintaining row spacing at 0.36 m under weed-free conditions resulted in *B. carinata* seed yield of 2,761 kg ha^{-1} when planted in mid-November (Mulvaney et al., 2019). Perhaps if *B. carinata* were planted in mid-November, as in the second year of the current study, a similar yield of 2,417 kg ha^{-1} and 2,520 kg ha^{-1} could be obtained after summer fallow and peanut, respectively (Figure 2-5). The low seed yield in 2018-2019 could be the result of late planting of *B. carinata* and a shorter growing season. Furthermore, although *B. carinata* seed yield without *S*-metolachlor was 2,284 kg ha^{-1} for 2019-2020, there was no effect of the weed management treatment on seed yield. This result suggests that winter *B. carinata* could be competitive against winter weeds and provide weed suppression without substantially compromising yield.

Implications of *Brassica carinata* for Integrated Weed Management

Weed population dynamics are expected to vary based on crop history, rotation, and management practices. Research on weed population simulation models have illustrated that the variation of crops in rotations can affect weed populations dynamics over the years (Jordan et al., 1995). After introducing *B. carinata* into the existing crop rotation, not only there will be impacts on the population of winter weeds, including ones that will interfere with *B. carinata*, but also on summer weeds, such as establishment, and timing and duration of the growing season.

Brassica carinata exhibited weed tolerance/suppression when grown without *S*-metolachlor yielding similarly to when *S*-metolachlor was applied to reduce weed populations. Therefore, it seems that weed control, early during the growing season, will suffice to give time to *B. carinata* to reach canopy closure and outcompete weeds,

especially those that are late-emerging species. This strategy has the benefit that does not eliminate the emergence and establishment of winter weed species, thus maintaining plant diversity and associated ecosystem services in the field without jeopardizing the yield goals (Petit et al., 2015).

A major finding of the present research is that *B. carinata* can decrease densities of some problematic summer weed species in the subsequent crop. The reduction of the seed bank that is germinable at the beginning of the summer cropping season can influence weed management, particularly for low inputs weed control systems (Teasdale et al., 2004). Having a shorter summer season for cash crops after *B. carinata* may not be a feasible option for growers to implement this strategy every year. However, *B. carinata* could be strategically grown once every few years to reduce summer weed seed banks and combine this practice with double cropping with late-planted crops e.g., soybean or sorghum [*Sorghum bicolor* (L.) Moench] to maintain economic viability. Crop rotation has been a vital component for effective weed control, and most importantly for the herbicide-resistance management (Beckie, 2006; Chauvel et al., 2001; Owen, 2008). Integrated weed management systems by incorporating *B. carinata* possess the potential to reduce herbicide use (and associated costs) and contribute for more stable weed management in the long term (Swanton and Weise, 1991). Overall, this approach would allow farmers diversify their crop rotation by including biofuel crop and develop a more robust integrated weed management strategy that will also help for herbicide-resistance management.

Table 2-1. Total rainfall and mean air temperature for 2018-2019 and 2019-2020 during and after *Brassica carinata* growing seasons.[a]

Months	Total Rainfall		Mean Temperature	
	2018-2019	2019-2020	2018-2019	2019-2020
	--------------------mm[b]----------------		-------------- °C[b]----------------	
November	201	20	13	13
December	336	156	12	12
January	84	162	10	12
February	46	178	16	13
March	51	40	15	19
April	140	55	19	19
May	82	92	24	22
June	141	210	26	25
July	95	261	27	26
August	187	134	26	26
Total/Mean[c]	1363	1308	18.8	18.7

[a]Data were obtained from the Florida Automated Weather Network (FAWN) located at the University of Florida/IFAS West Florida Research and Education Center in Jay, FL.
[b]Abbreviations: mm, millimeters; °C, degree Celsius.
[c]Total is presented for rainfall, but the mean is presented for temperature.

Table 2-2. Analysis of variance for the effects of crop history, weed management treatments, and their interactions on winter and summer weed species emergence during the *Brassia carinata* growing season.[a]

Year	Source of variation	df[b]	Chickweed	Cutleaf evening-primrose	Henbit	Sicklepod	Smooth pigweed
			--p-value[b]--				
2018-2019	Crop History (CH)	2	0.37	0.72	0.01	0.001	0.23
	Weed Management (WM)	2	0.01	0.07	0.02	0.83	0.004
	CH × WM	4	0.69	0.29	0.20	0.29	0.64
2019-2020	Crop History	2	0.001	0.29	0.01	0.02	0.10
	Weed Management	2	0.26	0.53	<0.0001	<0.0001	<0.0001
	CH × WM	4	0.94	0.89	0.39	0.31	0.50

[a]Data were combined over 2018-2019 and 2019-2020 seasons.
[b]Abbreviations: df, degrees of freedom; p-value, probability value.

Table 2-3. Analysis of variance for the effects of crop history, weed management, and their interactions on *Brassica carinata* biomass and yield.[a]

Source of Variation	df[b]	Biomass		Yield	
		2018-2019	2019-2020	2018-2019	2019-2020
		--------------------------------p-values[b]---------------------------			
Crop History (CH)	2	0.025	0.037	0.262	0.021
Weed Management (WM)	2	0.064	0.522	0.261	0.379
CH × WM	4	0.528	0.821	0.189	0.896

[a]Data were combined over 2018-2019 and 2019-2020 seasons.
[b]Abbreviations: df, degrees of freedom; p-value, probability value.
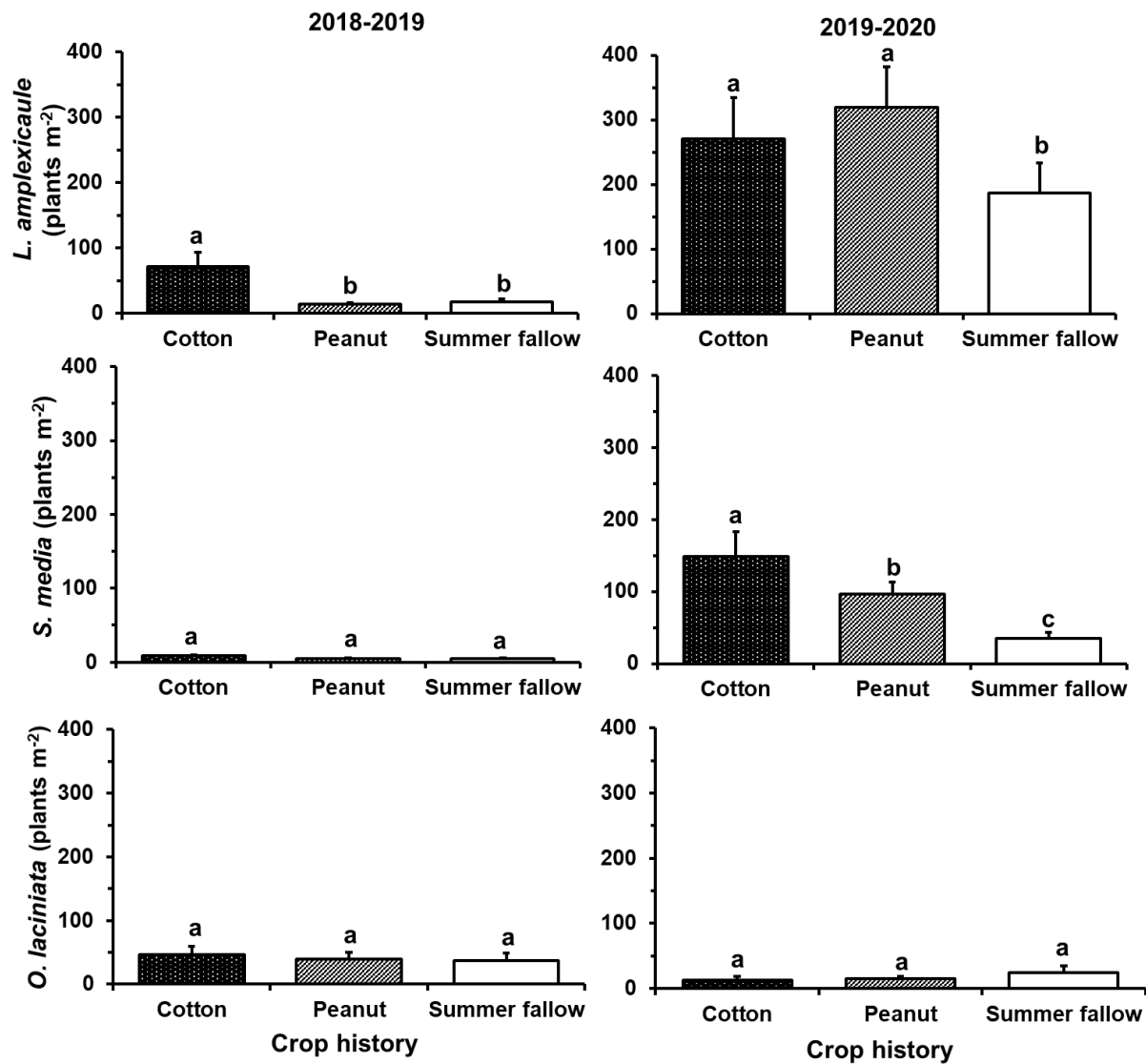
Figure 2-1. Effect of crop history (cotton, peanut, and summer fallow) on *Lamium amplexicaule*, *Stellaria media*, and *Oenothera laciniata* emergence in 2018-2019 and 2019-2020. Error bars represent the standard errors of the means. Treatments with the same letter within year and species are not significantly different (α = 0.05).
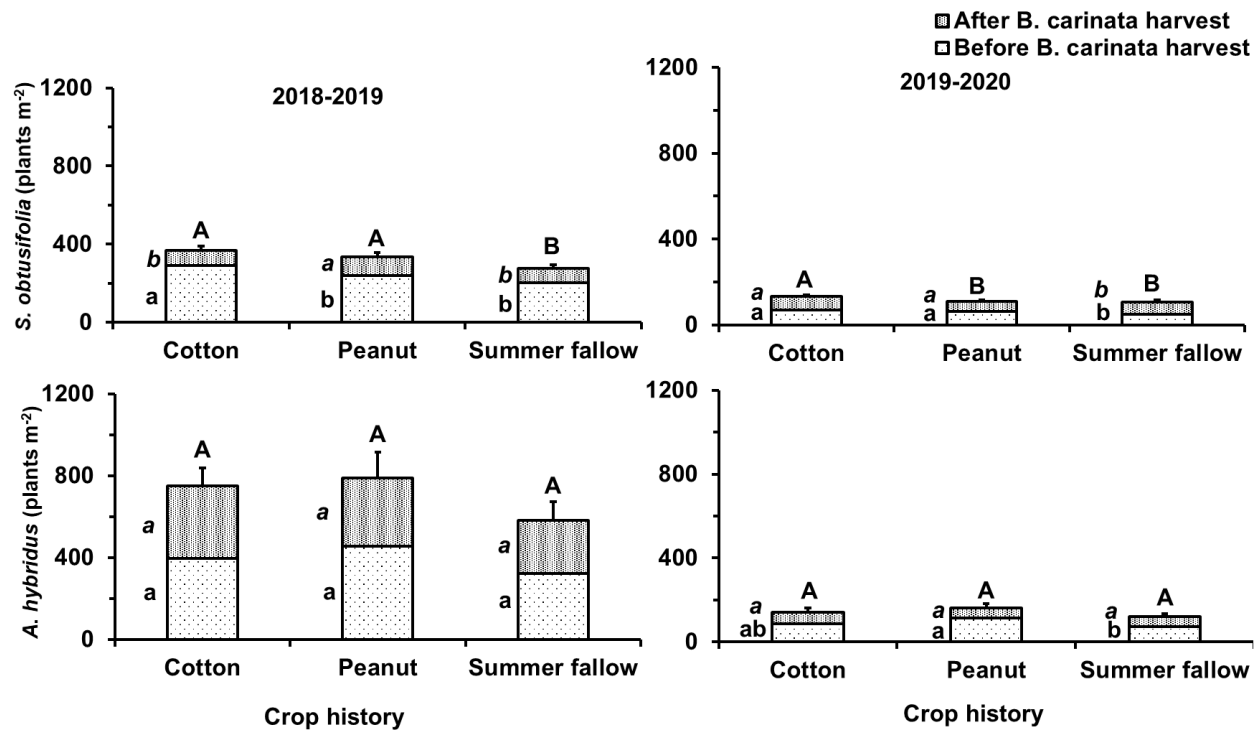
Figure 2-2. Effect of crop history (cotton, peanut, and summer fallow) on *Senna obtusifolia* and *Amaranthus hybridus* emergence before (February-June and November-May) and after (July-September and June-August) *Brassica carinata* harvest in 2018-2019 and 2019-2020. Error bars represent the standard errors of the means where treatments with the same letter (capitalized at the top of each graphs) within year and species are not significantly different (α=0.05). Regular and italicized letters indicate differences between treatments before and after *B. carinata* harvest, respectively.
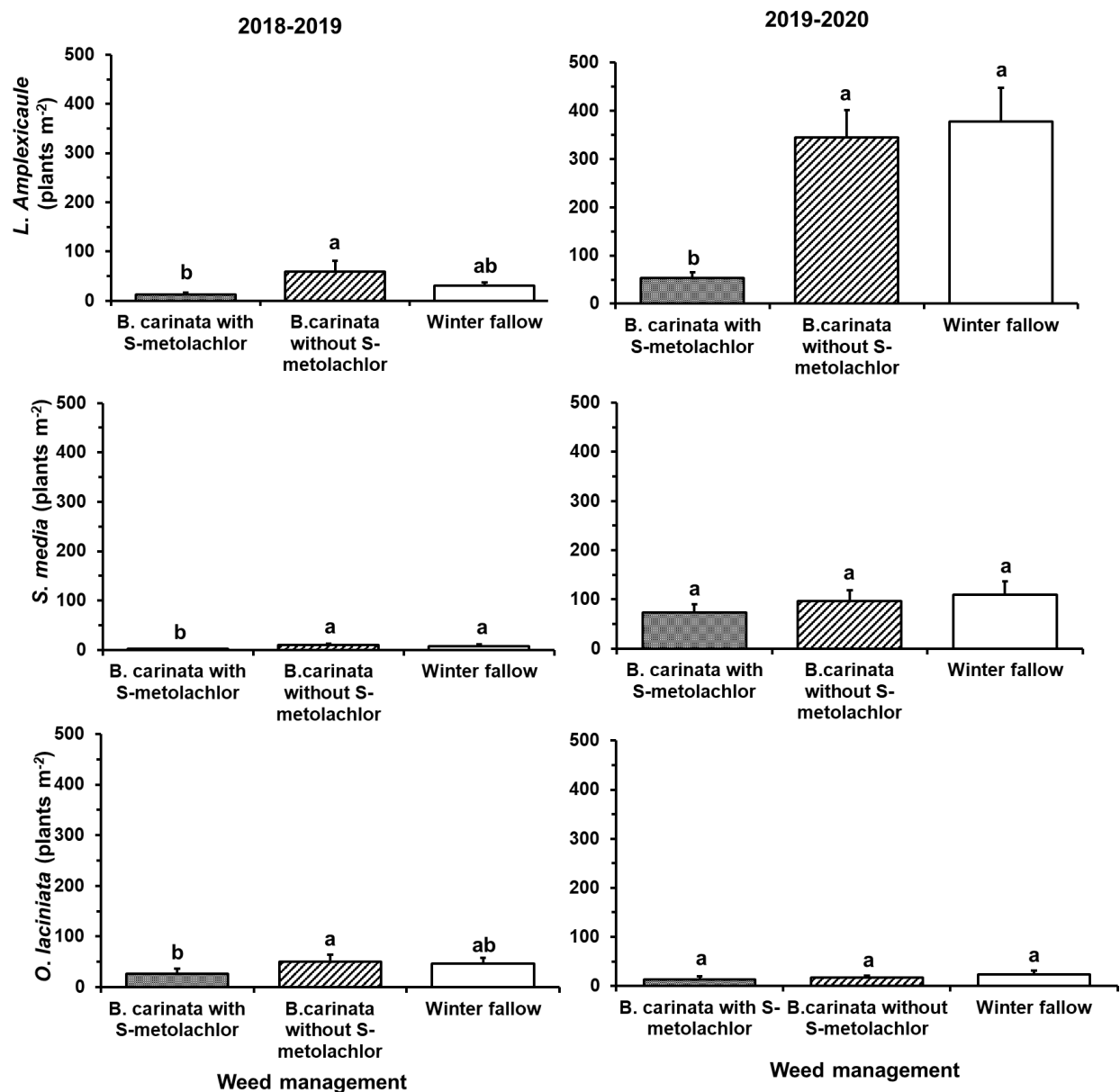
Figure 2-3. Effect of weed management treatments on *Lamium amplexicaule*, *Stellaria media*, and *Oenothera laciniata* emergence in 2018-2019 and 2019-2020. Error bars represent the standard errors of the means. Treatments with the same letter within year and species are not significantly different (α = 0.05).
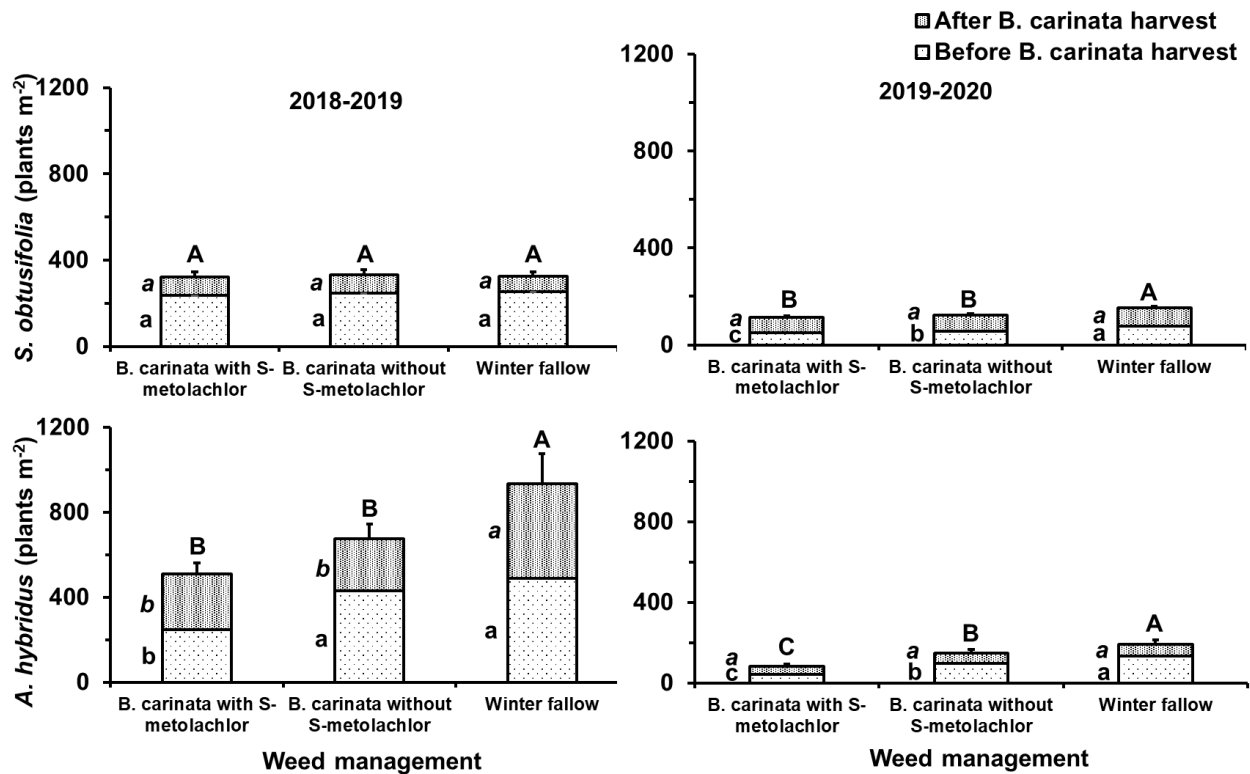
Figure 2-4. Effect of weed management treatments on *Senna obtusifolia* and *Amaranthus hybridus* emergence before (February-June and November-May) and after (July-September and June-August) *Brassica carinata* harvest in 2018-2019 and 2019-2020. Error bars represent the standard errors of the means where treatments with the same letter within year and species are not significantly different (α = 0.05). Regular and italicized letters indicate differences between treatments before and after *B. carinata* harvest, respectively and capital letters at the top of each graph represent differences between treatments.
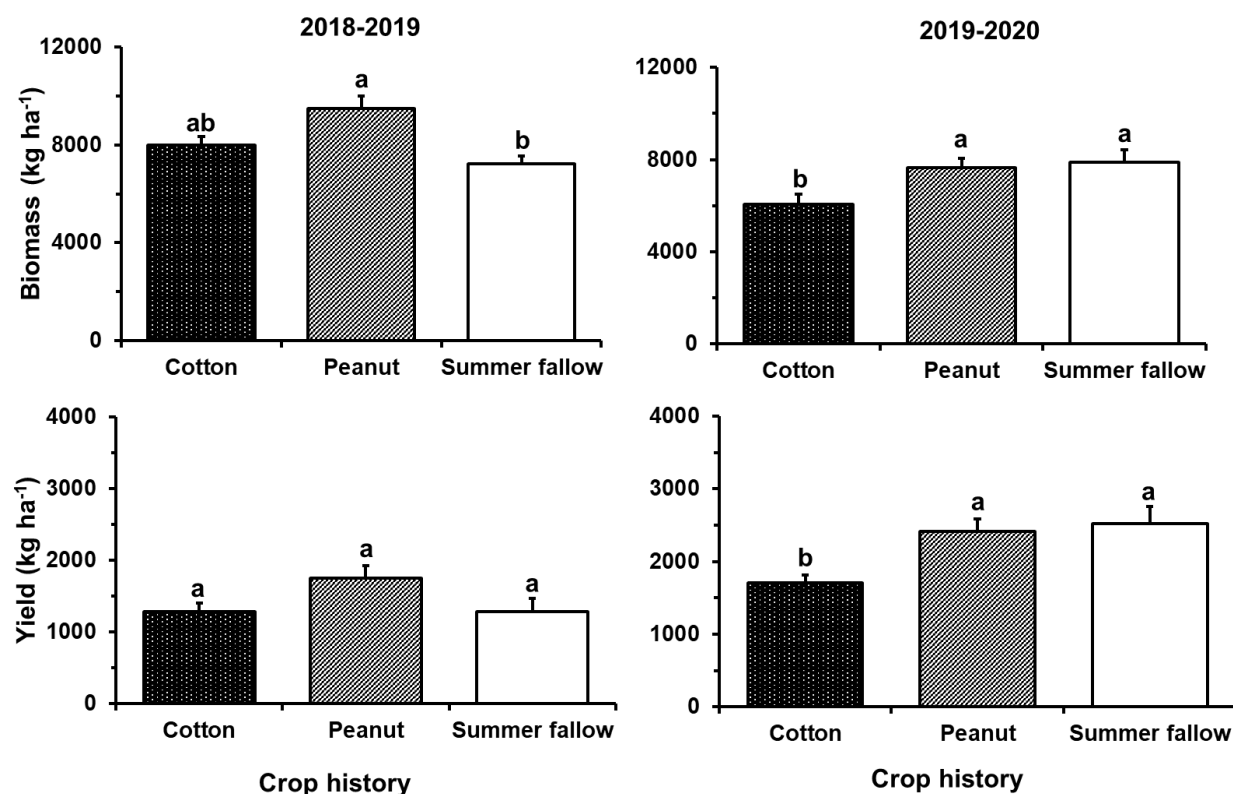
Figure 2-5. Effect of crop history (cotton, peanut, and summer fallow) on *Brassica carinata* biomass and seed yield in 2018-2019 and 2019-2020. Error bars represent the standard errors of the means. Treatments with the same letter within the year are not significantly different (α = 0.05).

CHAPTER 3
EMERGENCE PATTERNS OF WINTER AND SUMMER ANNUAL WEEDS IN
BRASSICA CARINATA CROPPING SYSTEMS

Summary

Brassica carinata A. Braun is a biofuel crop that was recently introduced in the southeast United States. In order for this crop to be successful, there is a need to develop integrated weed management strategies that complement its rotation with summer cash crops. The objectives of this research were to evaluate the effect of previous season summer crops on winter weed emergence patterns during *B. carinata* growing season and to assess the impact of planting *B. carinata* on the emergence patterns of summer weed species. Gompertz models were fit to winter and summer weed emergence patterns. All models represented more than 80% of the variation with RMSE values less than 0.20. The emergence pattern for winter weed species was best described using Growing Degree Days (GDD) accumulation and this model can be utilized for implementing weed control strategies at the critical *B. carinata* growth stages. The results also showed that summer weeds can emerge during the winter in northern Florida but do not survive frost damage, which might create off-season seed bank reduction before the summer crop growing season.

Introduction

Ethiopian mustard (*Brassica carinata* A. Braun) originated from the natural and hybridization between black mustard [*Brassica nigra* (L.) Koch.] and wild cabbage (*Brassica oleracea* L.). *Brassica carinata* has been recently introduced as a non-edible, winter oilseed crop in the southeastern United States for biofuel production (Cardone et al., 2003; Seepaul et al., 2019b). Approximately 0.10 million ha of land are suitable for producing *B. carinata* in Florida and can help meet the current demand for renewable

energy (Alam and Dwivedi, 2019). Besides their potential for oil production, Brassicaceae species have been considered good options for crop rotation because of their ecological services: a deep taproot to break up compacted soils and scavenge nutrients, a wider canopy to suppress weeds, and attractive flowers for pollinators (Alcántara et al., 2009; Brown, 1997; Díaz et al., 2013; Haramoto and Gallandt, 2004; Manning and Wallis, 2005; Rahman et al., 2018).

Since *B. carinata* is a new crop in the US southeastern region, researches are ongoing to evaluate basic agronomic practices including, planting strategies, nutrient management, and identification of genotypes suitable to the region (Kumar et al., 2020; Mulvaney et al., 2019). Regarding weed management, herbicides registered for other crops have been evaluated for *B. carinata* tolerance, but this research has only identified a few herbicides that can be safely used in this crop (Leon et al., 2017). Therefore, greater understanding about winter weed behavior in *B. carinata* will aid in the selection and implementation of options/strategies for integrated weed management.

As demonstrated by wide-spread infestations of herbicide-resistant weeds in summer crops, over reliance on a single technology (i.e., herbicides) not only threatens economic viability, but also ecological sustainability of agro-ecosystems (Busi et al., 2013). The use of integrated strategies which incorporate several tools, including crop rotation systems, is imperative for the sustainable weed management. Thus, growers might benefit from growing *B. carinata* in winter to complement existing crop rotations. Moreover, growers might be more willing to grow *B. carinata* if its addition to the existing

crop rotation can contribute to overall weed seed bank management for subsequent crop growing seasons.

Weed management decisions could be improved by predicting weed emergence timing and increasing the efficiency of weed control tactics, particularly during the vulnerable crop stages (Forcella et al., 2000; Leon et al., 2015; Myers et al., 2004; Reinhardt Piskackova et al., 2020a; 2020b). Soil environmental conditions such as soil temperature and moisture can influence weed seedling emergence intensity and timing, thus these factors are critical components for planning and successful implementation of integrated weed management strategies (Calado et al., 2009; Deen et al., 2001; Hartzler et al., 1999; Shaner and Beckie, 2014). Currently, no research has been conducted to identify the emergence patterns of winter and summer annual weeds in *B. carinata* cropping systems in the southeastern region of US.

In the present study, we hypothesized that crop history and weed management treatments affect the emergence pattern of winter and summer annual weed species in *B. carinata*. Therefore, the objectives of this research were 1) to determine the effect of previous summer crops on the emergence of winter weed species, and 2) to evaluate the effect of planting *B. carinata* in the winter and its influence on the emergence patterns of summer weed species in the subsequent season.

Materials and Methods

Site Description

Field research was conducted at the University of Florida/IFAS West Florida Research and Education Center, Jay, FL (30˚46'37" N 87˚8'20" W) from May 2018 to September 2019 (2018-2019) and May 2019 to July 2020 (2019-2020). For the 2018-2019 site, the soil included a Dothan loamy sand (fine-loamy, kaolinitic, thermic Plinthic

Kandiudult) with pH 6.3 and an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult) with pH 6.0. The sites during the 2019-2020 season were a mosaic of Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudult) with pH 6.0 and Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) with pH 5.8.

Experimental Design

The experiment was a split-plot arrangement in a randomized complete block with seven and eight replications in the 2018-2019 and 2019-2020 seasons, respectively. The main plot was the crop in the preceding summer growing season (i.e., crop history): 1) cotton (*Gossypium hirsutum* L.) (DP1646); 2) peanut (*Arachis hypogea* L.) (Georgia-06G); and 3) weed-free fallow. The sub-plot was weed management during the *B. carinata* growing season: 1) *B. carinata* (Avanza 641) with preemergence (PRE) applied *S*-metolachlor at 1,420 g a.i. ha^{-1}, (Dual Magnum, Syngenta Crop Protection, Greensboro, NC, USA); 2) *B. carinata* without *S*-metolachlor; and 3) weedy winter fallow. The main plots were 11 m long by 22 m wide, and sub-plots were 11 m long by 7 m wide. Seeds of *Senna obtusifolia* (L.) H.S.Irwin & Barneby were collected from natural populations at the West Florida Research and Education Center in 2018 and obtained from Azlin Seed Service (Leland, MS) for the 2019-2020 season. *Amaranthus hybridus* (L.) seeds were obtained from Azlin Seed Service for both years. Three 1-m^2 quadrats were randomly placed within each sub-plot before planting *B. carinata*. *Senna obtusifolia* seeds were spread at 2,000 seeds m^{-2} in November 2018 and 3,500 seeds m^{-2} in November 2019 in one of the quadrats. Likewise, *A. hybridus* seeds were spread at 25,000 seeds m^{-2} for both years in another quadrat, while the third quadrat was left for tracking the emergence of natural seed bank of the winter weeds, *Lamium amplexicaule* L., *Stellaria media* (L.) Vill, and *Oenothera laciniata* Hill.

Field Maintenance

The site was maintained during the summer (prior to *B. carinata* growing season) by planting cotton, peanut, or left fallow according to the main plot factors. The summer fallow treatment was regularly treated with glyphosate (RoundUp PowerMax, Bayer CropSciences, USA) at 1,156 g a.i. ha-1 throughout the summer to control the natural weed community characterized predominantly by *S. obtusifolia*, *A. hybridus*, *Desmodium tortuosum* (Sw.) DC., *Commelina benghalensis* L., *Eleusine indica* (L.) Gaertn., *Echinochloa crus-galli* (L.) P.Beauv. All the agronomic and weed management practices for cotton and peanut were followed according to the local recommendations (Ferrell et al. 2020a; Ferrell et al. 2020b; Wright et al. 2016; Wright et al. 2017). After harvesting cotton and peanut, fields were disked twice, roto-tilled, summer weed seeds were spread in the respective 1-m2 quadrats and lightly cultivated before planting *B. carinata*. *Brassica carinata* was planted on February 4, 2019, for the 2018-2019 season and on November 18, 2019, for the 2019-2020 season with a seeding rate of 6 kg ha-1 and 36 cm row spacing by using a grain-drill planter (Great Plains 1206 NT, Salina, KS). Planting was done only in the sub-plot treatments with *B. carinata* plus *S*-metolachlor and *B. carinata* without *S*-metolachlor. In 2018-2019, although earlier planting was planned, heavy and frequent rainfall events caused a delay in *B. carinata* planting until February 2019 (Table 2-1). For *B. carinata* with S-metolachlor treatment, herbicide was applied immediately after planting with a tractor-mounted sprayer calibrated to deliver at 187 L ha-1 using XR11002 (TeeJet Technologies, Wheaton, IL, USA) nozzle. Liming and fertilization were done according to soil tests results and based on recommendations for canola (*Brassica napus* L.), except for N, which was applied at 22

kg N ha-1 as urea immediately after planting, and additional 68 kg N ha-1 were top-dressed at early bolting.

Weed Seedling Emergence and Data Collection

After planting *B. carinata*, emerged *S. media*, *O. laciniata*, and *L. amplexicaule* seedlings were counted in the designated 1-m^2 quadrats and hand removed on a weekly interval throughout the *B. carinata* growing season from February 4 to April 8, 2019 for 2018-2019 and November 18, 2019 to April 10, 2020 for 2019-2020 seasons. Summer annual weed species (*S. obtusifolia* and *A. hybridus*) seedling emergence was detected during the winter from November to February. This winter, emergence was recorded in the respective 1-m^2 quadrats and hand removed every week throughout the *B. carinata* growing season. After *B. carinata* harvest, the emergence of two summer weed species continued and was recorded throughout the subsequent summer until emergence ceased. Soil moisture and temperature data were recorded every 30 minutes at 7 cm depth in the experimental site in the main-plots for 2018-2019 and 2019-2020 seasons using 12-bit temperature and ECH20 EC-5 soil moisture sensors, and HOBO U30 data loggers (Onset Computer Corporation, Bourne, MA, USA).

Emergence Pattern Modeling

Calculation of relative cumulative emergence for *S. media*, *O. laciniata*, and *L. amplexicaule* was done per quadrat as a percent of total emergence during *B. carinata* growing season. Similarly, the relative cumulative emergence for *S. obtusifolia* and *A. hybridus* were calculated up to *B. carinata* harvest time and continued throughout the summer until the emergence of weed weed emergence ceased. Thermal time was used to describe emergence patterns using cumulative growing degree days (GDD) which is represented by the following equation:

$$GDD = \sum_{i=1}^{n}(T_{mean} - T_{base}) \tag{3-1}$$

where T_{mean} represents the daily mean soil temperature in C, and T_{base} is the minimum temperature at which *S. media*, *O. laciniata*, *L. amplexicaule*, *S. obtusifolia*, and *A. hybridus* seeds germinate. The base temperature was 10 C for *S. media*, 0 C for *O. laciniata* and *L. amplexicaule*, and 15 C for *S. obtusifolia* and *A. hybridus* (Creel et al., 1968; Grundy et al., 2000; Guo and Al-Khatib, 2003; Hill et al., 2014; Patterson, 1993; Teem et al., 1980; Wright et al., 1999). Cumulative thermal time (GDD) was calculated beginning at soil preparation for the winter annual weeds and beginning January 1st for the summer annual weeds.

Thermal time models were developed to describe the observed cumulative weed emergence for each crop history: cotton, peanut, and summer fallow fitting the data to the Gompertz equation (Equation 2; Forcella et al., 2000) using SigmaPlot version 11 (Systat Software Inc., San Jose, CA , USA):

$$y = a * \exp(-\exp(-(x - x_0)/b)) \tag{3-2}$$

where *y* is the relative cumulative emergence for time *x*, *a* is the asymptote (theoretical maximum for *y* normalized to 100%), x_0 is the lag period before emergence begins, and *b* is the rate of emergence.

Each experimental unit of the study design generated an independent emergence set for every weed species tracked over the growing season. A total of 135 emergence sets were recorded for each species between the two study years. Each set needed to have cumulative emergence of at least 20 plants m^{-2} to be included in the analysis.

Preliminary analyses indicated that the interaction of crop history and weed management treatment was not significant (0.20<P<0.94) for all the weed species evaluated (data not shown) so only the main effects were modeled for weed emergence patterns. Models were developed for each crop history by pooling weed management treatments because although weed management treatments affected weed density (Tiwari et al., 2020), they did not modify emergence patterns (data not shown). After removing sets with less than 20 plants m^{-2} cumulative emergence, each winter weed species had 15 sets per crop history and each summer weed species had 45 sets per crop history. For both years, models were fit to 9 randomly selected sets of each crop history for *S. media*, *L. amplexicaule*, and *O. laciniata* and 30 randomly selected sets for *S. obtusifolia* and *A. hybridus* using PROC NLMIXED and PROC REG in SAS (SAS Institute, Cary, NC, USA). Akaike's information criterion (AIC) and root mean square error (RMSE) were used to compare the fitness of different models to the data set. The remaining sets for each crop history that were not used for modeling were used to validate the models: 6 and 15 sets for each winter and summer weed species, respectively. Regression (PROC REG) was done with the predicted values from fitted Gompertz models with the observed values of the validation data sets. This procedure is a robust method for describing weed emergence of the main-plot treatments with non-linear models (Hill et al., 2014). Additionally, to test if a single model adequately described all treatments, the model for summer fallow (control) was regressed with the validation data sets for other two crop history treatments. The summer fallow treatment did not receive fertilization or residual herbicides; therefore, it was considered as the crop history treatment that could provide the least biased assessment of weed seedling

emergence. The model generated for summer fallow was used for validation against the independent data sets from the other crop history data sets.

Brassica carinata Phenological Stages

Dates of important *B. carinata* growth stages were recorded. GDD were calculated for *B. carinata* using 5 C as base temperature based on winter canola (Vigil et al., 1997).

Results and Discussion

Winter Weed Emergence Model Fitness

In general, studied winter weeds showed defined emergence patterns across years and treatments. All the models had a good fit as demonstrated by very low AIC values (Table 3-2). Models for *O. laciniata* had AIC values less than -100 and *L. amplexicaule* and *S. media* less than -200. Another metric to evaluate fitness is the RMSE, which can be interpreted as a ratio of the data variation not described by the model. Thus, all models described more than 80% of the variation of the data. Based on these results, the reported models described well the emergence pattern of the three winter weed species following each crop history treatment.

While the emergence of studied winter weed species was described well with the model for each crop history treatment, the model parameters were very similar across crop histories (Table 3-2). Therefore, we evaluated whether a single model (i.e., summer fallow model) could be used to describe seedling emergence regardless of the crop history. The summer fallow model was validated with independent weed emergence data from the cotton and peanut crop history treatments, and more than 80% of the emergence variation was properly described (Table 3-2). This provides evidence that seedling emergence patterns of the studied winter annual weed species

may not need to be adapted based on every crop history and weed management

strategy, rather they can be modeled primarily by accounting for soil temperature

(Figure 3-1; 3-2;3-3).

Emergence Timing and Sequence of Winter Weed Species During *Brassica carinata* Season

Brassica carinata is usually competitive after canopy closure, but weed control is

essential at early growth stages (Leon et al., 2017). Therefore, it is necessary to know

the critical time frame for winter weed species emergence within *B. carinata* season.

Cotton, peanut, and summer fallow crop history showed similar emergence

patterns for *S. media* (Figure 3-1). The summer fallow history model was an adequate fit

for all treatments, accounting for at least 90% of the variation (Table 3-2). According to

the summer fallow history model, *S. media* reached 50% emergence by 250 GDD i.e.

before *B. carinata* reached at 4 leaf stage (Figure 3-1). Likewise, majority of *B. carinata*

plants were at the 12-leaf stage at 500 GDD, when 90% of *S. media* emergence had

occurred (Figure 3-1).

The emergence of *O. laciniata* and *L. amplexicaule* surpassed 50% between

500-700 GDD (Figures 3-2; 3-3). The required GDD to attain a 50% emergence for

these weed species was almost twice as long as for *S. media* (Figures 3-2; 3-3). For

these weed species, 90% of emergence occurred between 1000 and 1200 GDD, which

was equivalent to approximately 85 to 90 days after planting (DAP; Figure 3-4) and

corresponded to the pre-bolting stage for *B. carinata* (Seepaul et al. 2019b).

Model Fitness of Summer Annual Weed Emergence

Models of *S. obtusifolia* emergence following each crop history exhibited

excellent fitness with AIC values all less than -600 and accounting for more than 90% of

the variation in the data (Table 3-3). Still, the emergence pattern seen in each crop history treatment was explained well by the model developed for the emergence following the summer fallow with RMSE validation values of 0.09 to 0.11 (Table 3-3). Based on these results, *S. obtusifolia* followed a consistent emergence pattern regardless of crop history or management that can be described well by a single model (Figure 3-5).

Emergence patterns of *A. hybridus* following each crop history adequately fit the models and these models which accounted for over 80% of the variation in the emergence (Table 3-3). Over 80% of the variation was also explained with the fallow model (Table 3-3). However, there was significant variation between sampling points (Figure 3-6). For example, in some quadrats, emergence reached 100% in 250 GDD while others took almost 1500-1700 GDD and no emergence was observed until the end of the summer season (Figure 3-6).

Emergence pattern is a function of seed dormancy release and the presence of adequate germination conditions, such as soil moisture, and temperature (Karseen and Bouwmeester, 1992; Roberts, 1964). In the present study, the winter weed species, which exhibit physiological dormancy, were able to release dormancy during the summer (Baskin and Baskin, 1976; Baskin and Baskin, 1981; Steiner, 1968; Taylorson and Hendricks, 1976) resulting in a uniform and well-defined sigmoidal emergence patterns (Figure 3-1; 3-2; 3-3)

Early Spring Emergence of Summer Weed Species

It was unexpected to see abundant seedling emergence of the two summer annual weeds (*S. obtusifolia* and *A. hybridus*) during the winter, which resulted in seedling mortality due to frost damage. However, from the end of January to April, there

were multiple days with temperatures above the base temperature for these weed species (Table 3-1), which could trigger the germination of non-dormant seeds. *Senna obtusifolia* non-dormant seeds germinate over a wide range of temperatures (Teem et al., 1980). This species possesses physical dormancy that was likely reduced by the scarification caused by cultivation in the fall, microbial activity, and temperature fluctuations (Baskin and Baskin, 2004). Meanwhile, *A. hybridus* (a small-seeded weed) possess physiological dormancy (Gallangher and Cardina, 1998), which is quickly reduced under moist cold conditions such as those present from December to February in the experimental area. Therefore, in northern Florida where temporary warm periods are not uncommon during the winter-spring transition, non-dormant *A. hybridus* seeds can germinate, but during the winter months these emergence events are not consistent due to the return of cold temperatures, which results in a variable emergence pattern as observed in the current study (Figure 3-6; Leon and Owen, 2006).

Approximately 11% of *S. obtusifolia* seeds initially placed in the quadrats emerged (average of the cumulative emergence) by *B. carinata* harvest, which was between 150-180 days after January, or mid-May to early-June for reference (Figure 3-5; Table 3-4). Also, the results showed less than 10% of *A. hybridus* from the previously added seeds resulted in emerged seedlings during *B. carinata* growing season (Table 3-4). More importantly, about 40% of the total emergence of *S. obtusifolia* occurred before planting summer crops (i.e., between 500 to 1000 GDD or between May to July; Figure 3-5). Therefore, almost half of the total season emergence was eliminated during the *B. carinata* growing season and prior to establishing summer crops (Figure 3-5). Different factors such as germination, seed decay, microbial infection, predation, and

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fatal germination could account for the loss of weed seeds in the soil and low seedling emergence (Buhler et al., 1997; Davis and Renner, 2007; Martinkova and Honěk, 2013; Murdoch and Ellis, 1992; Schwinghamer and Van Acker, 2008). Germinable and extractable weed seed bank analysis (Reinhardt and Leon, 2018) also showed few viable seeds for *S. obtusifolia* emergence at *B. carinata* harvest (data not shown), which indicated that there was an important reduction in the viable seed bank during winter-spring season. Therefore, winter-spring seedling emergence (during the *B. carinata* production season) could be an important source of pre-summer season population reduction for the two summer weeds currently studied.

Implications of Winter and Summer Weed Emergence

Winter weed emergence patterns illustrates the critical timing when growers can implement short term weed management options in *B. carinata* production season. *Stellaria media*, *O. laciniata*, and *L. amplexicaule* are prevalent winter weed species in the southeastern US. While predictive emergence models for these species can help in timing weed control, it is equally important to consider the relationship between weed emergence timing and crop growth to maximize both weed control efficacy and yield (Reinhardt Piskackova et al., 2020b). The results provided valuable information about seedling emergence patterns of three winter annual weed species during *B. carinata* growing season in the southeastern US. The best fit model proposed here can be used to predict the optimal timing of winter weed emergence and develop effective weed management strategies.

Emergence of summer annual weed species during the *B. carinata* growing period illustrates how weed management can be improved in a diversified crop rotation cycle on a long-term basis. When *B. carinata* was included as a winter crop into the

existing cotton-peanut rotation, a major proportion of the emerged *S. obtusifolia* and *A. hybridus* seedlings died before summer crops were planted. It is worth mentioning that well defined and consistent emergence patterns were not observed for the summer annual weed species in the present study due to temperature variability during the wintertime. Therefore, the thermal time models developed here are not likely to be useful to predict *S. obtusifolia* and *A. hyridus* emergence timing for summer crops, particularly because field preparation for planting (e.g., chemical burndown or cultivation) will reset the thermal time accumulation count. Despite this caveat, our models can be used to better understand weed seed bank and population dynamics of *S. obtusifolia* and *A. hybridus* in the subtropical condition such as that of the Florida panhandle. In addition, our results illustrate the importance of considering off-season seed bank dynamics for weed management.

Table 3-1. Average soil moisture and temperature for 2018-2019 and 2019-2020 cropping seasons.[a]

Months	Soil moisture[a]		Soil temperature	
	2018-2019	2019-2020	2018-2019	2019-2020
	---------------$m^3\ m^{-3}$---------------		------------------ °C-------------------	
November	-	0.17	-	16.38
December	-	0.21	-	14.41
January	0.24	0.24	11.94	13.83
February	0.26	0.24	16.74	14.63
March	0.27	0.13	17.49	19.59
April	0.27	0.18	21.02	21.45
May	0.24	0.15	25.82	25.08
June	0.23	0.19	27.55	29.63
July	0.30	0.26	28.02	28.59
August	0.30	-	29.12	-
September	0.25	-	27.76	-
Average[b]	0.26	0.19	22.82	20.39

[a]Data were obtained from HOBO-U30 data loggers' moisture and temperature sensors installed at the experimental site at the University of Florida/IFAS-West Florida Research and Education Center.
[b]Average soil moisture and temperature for 2018-2019 and 2019-2020 cropping seasons.

Table 3-2. Relationship between thermal time (cumulative GDD) and henbit (*Lamium amplexicaule*), cutleaf evening-primrose (*Oenothera laciniata*), and chickweed (*Stellaria media*) cumulative seedling emergence described with Gompertz models. A summer fallow predictive model was validated with independent data from three crop histories.

Weed species	Crop history	A	b	x0	AIC[a]	RMSE[b]	R^{2b}	RMSE validation[c]
Henbit	Cotton	1	231	358	-515	0.13	0.87	0.14
	Peanut	1	277	454	-248	0.05	0.97	0.11
	Fallow	1	257	410	-308	0.12	0.88	0.12
Cutleaf evening-primrose	Cotton	1	216	581	-153	0.18	0.80	0.19
	Peanut	1	292	598	-124	0.08	0.96	0.09
	Fallow	1	274	663	-184	0.10	0.92	0.10
Chickweed	Cotton	1	107	204	-350	0.12	0.88	0.10
	Peanut	1	121	245	-314	0.08	0.95	0.08
	Fallow	1	117	244	-218	0.09	0.94	0.09

[a]AIC is the Akaike's Information Criterion used for comparing models. The more negative values are the better fit.
[b] RMSE and R^2 reflects the fit of Gompertz equation used to create the model.
[c]Validation was done by comparing the predictive equation for fallow with validation data sets of each of the crop history treatments.

Table 3-3. Relationship between thermal time (cumulative GDD) and smooth pigweed (*Amarathus hybridus*) and sicklepod (*Senna obtusifolia*) cumulative seedling emergence described with Gompertz models. A summer fallow predictive model was validated with independent data from three crop histories.

Weed species	Crop history	a	b	x0	AIC[a]	RMSE[b]	R[2b]	RSME validation[c]
Smooth pigweed	Cotton	1	769	160	-29	0.15	0.81	0.15
	Peanut	1	778	268	-134	0.19	0.70	0.19
	Fallow	1	752	362	-99	0.13	0.87	0.13
Sicklepod	Cotton	1	460	527	-812	0.09	0.93	0.10
	Peanut	1	524	604	-1077	0.11	0.90	0.11
	Fallow	1	489	614	-680	0.09	0.94	0.09

[a]AIC is the Akaike's Information Criterion used for comparing models. The more negative values are the better fit.
[b]RMSE and R^2 reflects the fit of Gompertz equation used to create the model.
[c]Validation was done by comparing the predictive equation for fallow with validation data sets of each of crop history treatments.

Table 3-4. Percentages of seedlings emergence of smooth pigweed (*Amaranthus hybridus*) and sicklepod (*Senna obtusifolia*) during and after winter crop (*Brassica carinata*) growing season.[a]

Weed species	Crop history	During winter crop		After winter crop	
		2018-2019[a]	2019-2020	2018-2019	2019-2020
		------------------------------%--------------------------------			
Smooth pigweed	Cotton	2 a[b]	0.3 ab	1 a	0.2 a
	Peanut	2 a	0.5 a	1 a	0.2 a
	Fallow	1 a	0.3 b	1 a	0.2 a
Sicklepod	Cotton	15 a	2 a	4 b	2 a
	Peanut	12 b	2 a	5 a	1 a
	Fallow	10 b	1 b	4 b	2 a

[a]Seedling emergence percentage in relation to seeds initially placed in the 1 m^2 quadrats. Data were taken from the UF/IFAS-WFREC for 2018-2019 and 2019-2020 cropping seasons at Jay, FL.
[b]Same letters assignment within column indicates a non-significant difference for the percentages of emerged weed among the crop history for both the seasons based on Fishers Least Significant Difference (LSD) at (α = 0.05).

Figure 3-1. Relationship between a thermal time (cumulative GDD) model of *Stellaria media* seedling emergence, and independent sets of emergence data during the winter in fields that had cotton (orange square), peanut (blue circle), and non- crop fallow (green triangle) during the previous summer.

Figure 3-2. Relationship between a thermal time (cumulative GDD) model of *Oenothera laciniata* seedling emergence, and independent sets of emergence data during the winter in fields that had cotton (orange square), peanut (blue circle), and non- crop fallow (green triangle) during the previous summer.
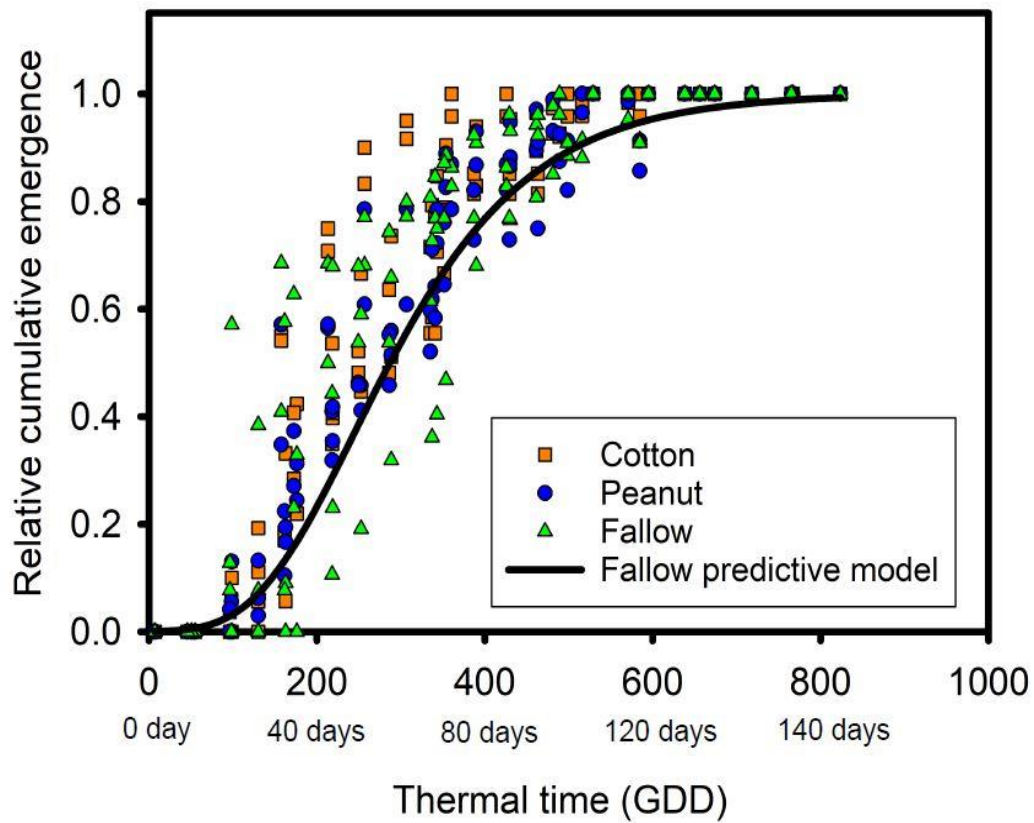
Figure 3-3. Relationship between a thermal time (cumulative GDD) model of *Lamium amplexicaule* seedling emergence, and independent sets of emergence data during the winter in fields that had cotton (orange square), peanut (blue circle), and non- crop fallow (green triangle) during the previous summer.
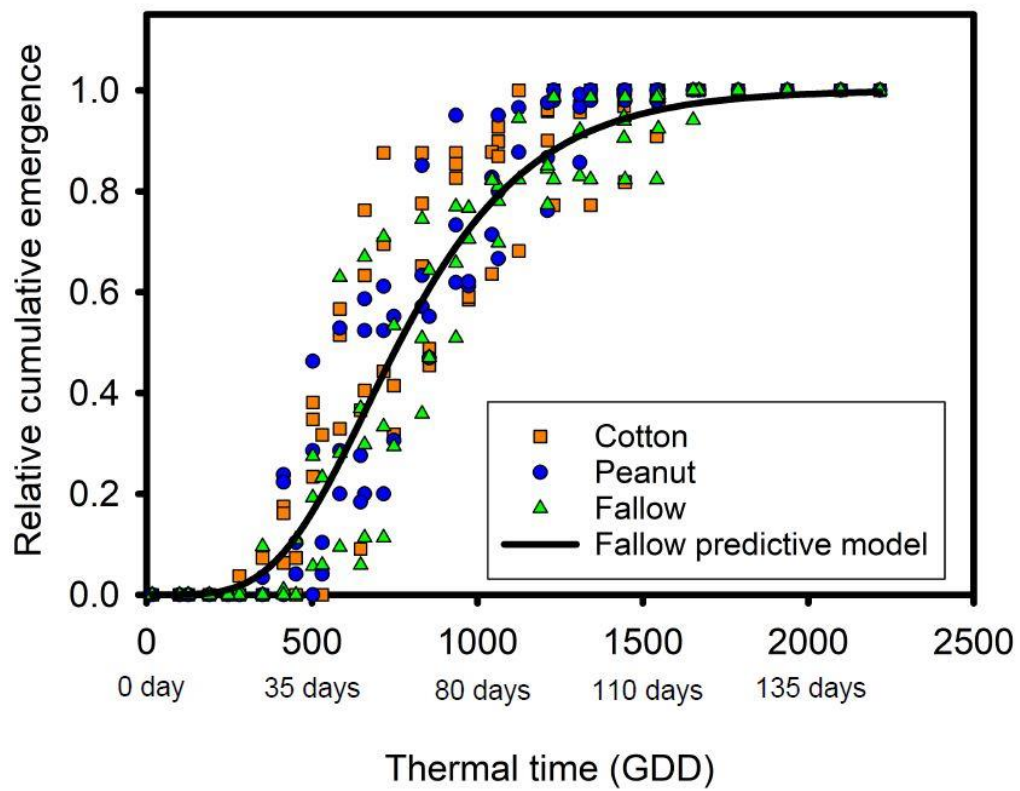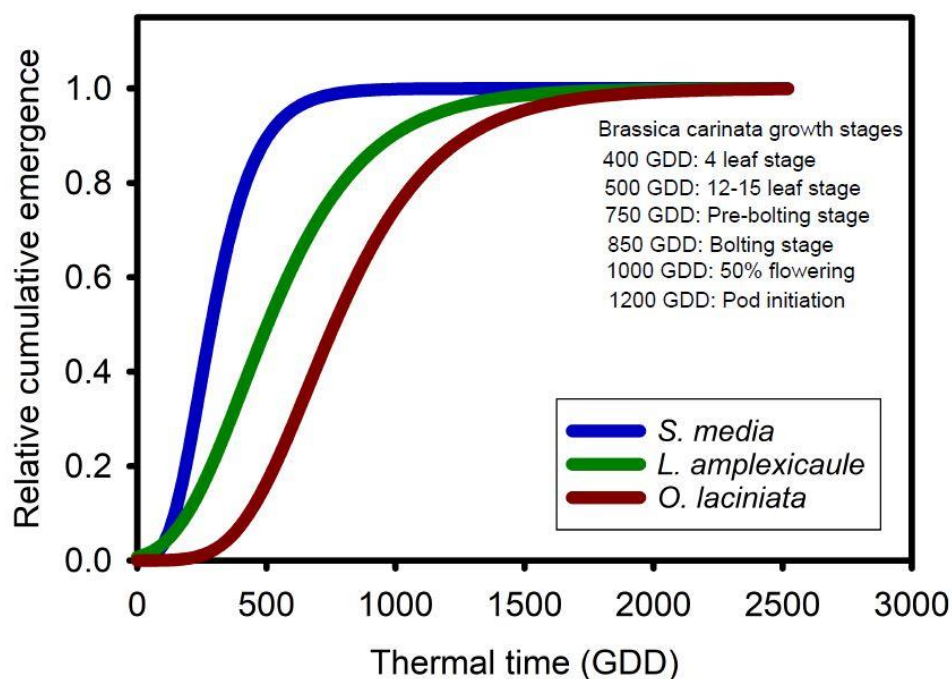
Figure 3-4. Relationship between a thermal time (cumulative GDD) model developed from the predicted sets from previous summer non-crop fallow for *Stellaria media* (blue solid line), *Lamium amplexicaule* (green solid line), and *Oenothera laciniata* (grey solid line) seedling emergence during *Brassica carinata* growing season. Phenological stages of fall planted *B. carinata* mentioned on the top right with the corresponding Growing Degree Days (GDD) at the experimental site at Jay, FL.
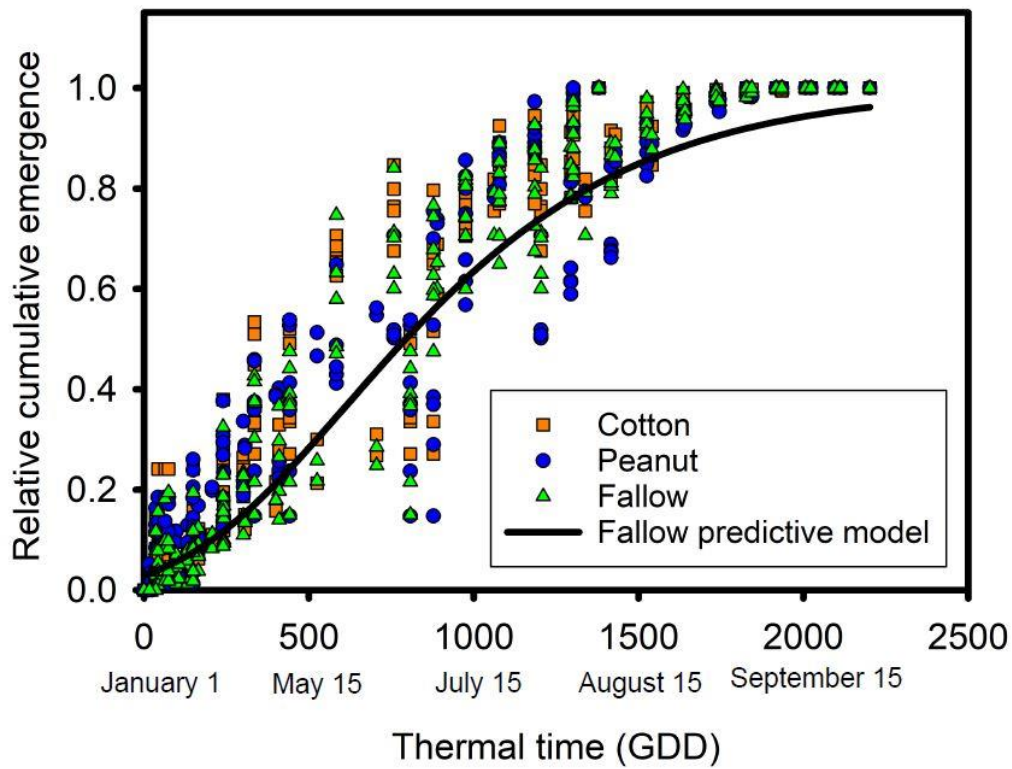
Figure 3-5. Relationship between a thermal time (cumulative GDD) model of *Senna obtusifolia* seedling emergence, and independent sets of emergence data during and after *Brassica carinata* season in fields that had cotton (orange square), peanut (blue circle), and non-crop fallow (green triangle) during the previous summer.
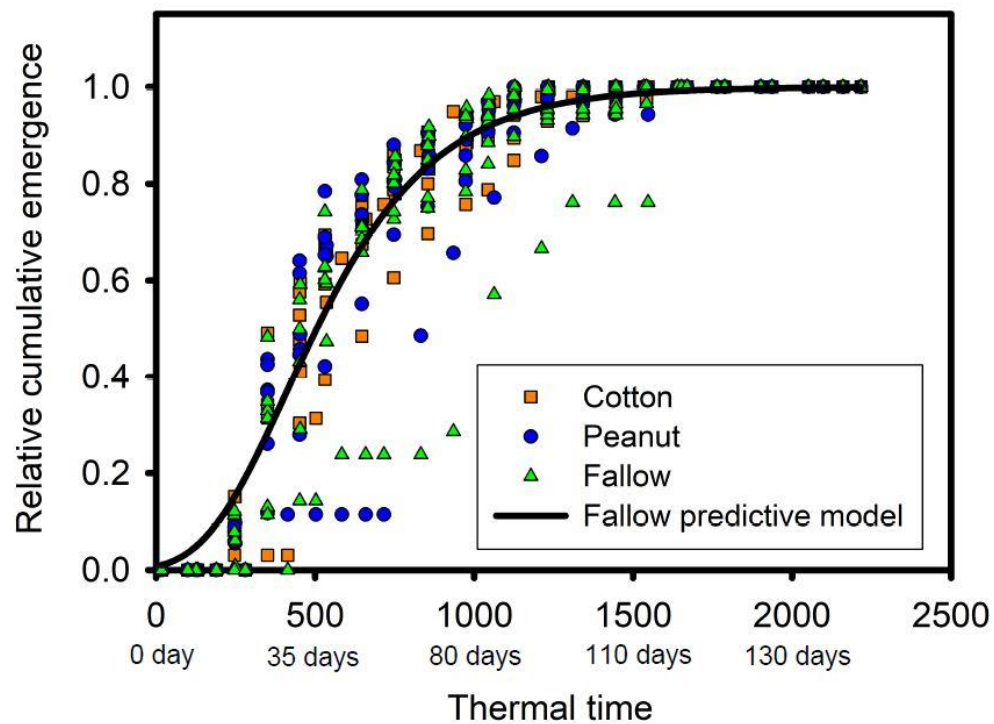
Figure 3-6. Relationship between a thermal time (cumulative GDD) model of *Amarathus hybridus* seedling emergence, and independent sets of emergence data during and after *Brassica carinata* season in fields that had cotton (orange square), peanut (blue circle), and non-crop fallow (green triangle) during the previous summer.
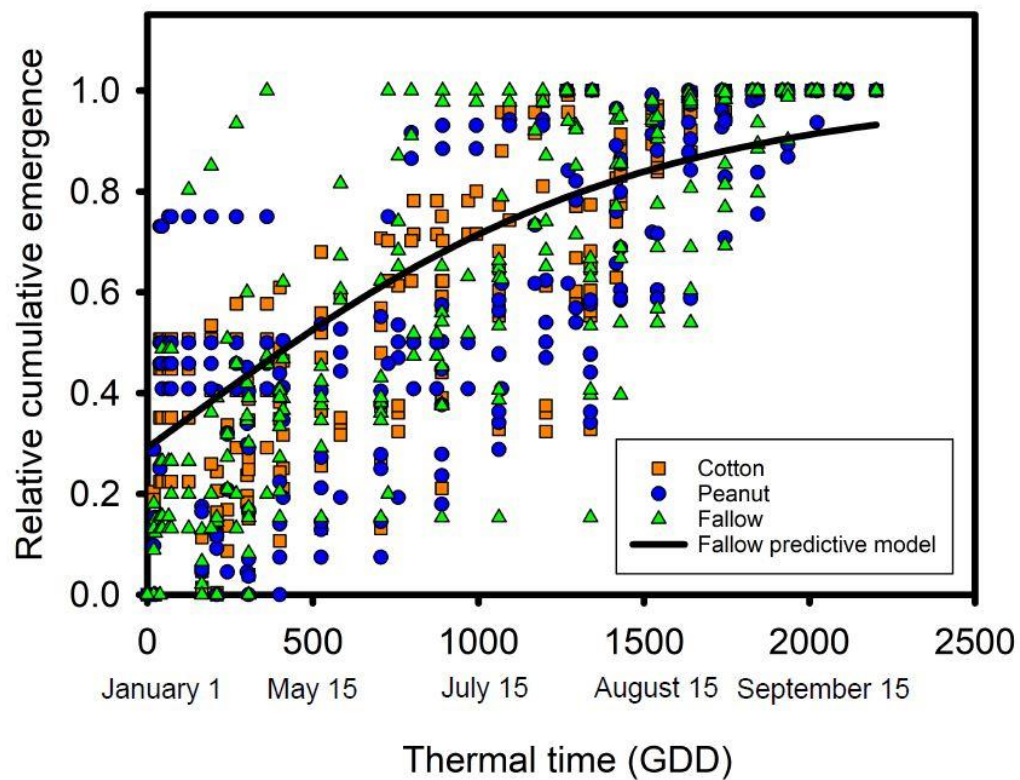
CHAPTER 4
GENERAL CONCLUSIONS

Cotton had a significant effect on *L. amplexicaule* and *S. obtusifolia* emergence compared to the summer fallow during *B. carinata* growing season. Crop history affected the density of emerged weed seedlings.

S-metolachlor application reduced *L. amplexicaule* population compared to the winter weedy fallow. This herbicide also reduced the emergence of *A. hybridus* compared to the herbicide-free *B. carinata* and the winter weedy fallow. *S*-metolachlor mitigated the pressure of weed and the risk of interference with *B. carinata*.

Even in the absence of *S*-metolachlor, *B. carinata* decreased *A. hybridus* and *S. obtusifolia* emergence during its growing season highlighting its potential for weed suppression. Moreover, even though the winter weeds density were higher in the *S-metolachlor*-free treatments, *B. carinata* biomass and seed yield were unaffected, reflecting its competitive ability over the studied weed species.

Even though weed density was altered, weed emergence timing was not affected by crop history or weed management. One model could be used to describe each weed species emergence with over 80% accuracy, regardless of treatment.

Research on integrated weed management in *B. carinata* will be beneficial for the farmers to reduce herbicide and related costs while contributing for robust weed management in a diversified crop rotation besides producing biofuel. Predictive emergence models for winter weed species developed in the present research will help increase weed control efficacy by relating weed emergence timing and winter *B. carinata* growth. The best fit model proposed can help farmers to predict the optimal timing of winter weed emergence in *B. carinata* and develop better short-term weed

management strategies. The proposed summer weed emergence pattern can help to understand the processes of seed bank depletion. It is equally important to consider off-season seedbank dynamics process to manage the summer annual weeds. Knowledge on the summer annual weed emergence during *B. carinata* growing season highlighted importance for incorporating it in a crop rotation and improving weed management systems in the long-term.

More research is required evaluating *B. carinata* rotation in multiple cropping systems for developing integrated weed management strategies. In the future research, influence of *B. carinata* on other winter and summer weed population dynamics, besides the ones in this research, need to be studied. A long-term study evaluating germinable and extractable weed seed bank would help to determine if there is any shift in the weed populations. The current research highlighted more on the emergence patterns of winter weeds. Future work can include models based on the hydrothermal time to predict the phenology of winter weed species and the optimum timing for implementing control strategies. Newer technologies such as image analysis might be incorporated together in the similar future study to quantify the weed emergence and use this information for generating weed emergence models.

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