PLANTS OUT OF PLACE: BENEFITS AND CHALLENGES OF COVER CROP-BASED WEED MANAGEMENT IN GEORGIA AND THE SOUTHEAST US

by

DAVID WEISBERGER

(Under the Direction of Nicholas Basinger and Jennifer Jo Thompson)

ABSTRACT

The overarching goal of this dissertation was to evaluate the biophysical effects of integrated approaches to weed management, those that rely on practices in addition to herbicide-use, and to identify stakeholder perceptions of these approaches. Herbicide use is the primary, and often, exclusive, means of managing weeds within industrialized agronomic cropping systems. Given the scale at which these systems are operated, herbicide use represents the most effective and economically viable option for managing weeds. However, since the late 1960's there have been an increasing quantity of cases of herbicide resistance in almost all weeds of economic importance. Herbicide resistance can be considered an outcome of natural selection. Continued reliance on herbicide-dominant weed management will lead to more resistant weeds, and resistance to more herbicide modes of action. In the Southeast United States, herbicide resistant weeds have become an existential threat to agricultural productivity and economic livelihoods. Finding non-herbicidal methods of limiting weed populations are imperative. The use of cover crops, a cultural management practice, may aid in this effort. *Annual cover crops* are species of grasses and forbs (often repurposed cereal and legume crop species) that are usually planted and established in seasonal periods that are asynchronous to cash crop growth.

Herbicides and/or physical equipment are used to terminate annual cover crops, leaving a layer of residue into which a cash crop is then planted. *Living mulches* are variants of cover crops that are actively growing throughout the entire year. While both annual and perennial species have been used, the research described in this dissertation uses a perennial white clover species developed in Georgia called ‘Durana®.’ Using both meta-analyses and a structured plot experiment, we evaluated the potential of both cultural practices to suppress weeds. This biophysical research was coupled with the use of a Q-methodology study employed to identify and describe stakeholder perceptions on integrated weed management approaches, such as those described above. Collectively, this represents an interdisciplinary effort to explore both biophysical and social dimensions of integrated weed management in Georgia and the Southeast US.

INDEX WORDS: Cover crops, Human dimensions of pest management, Integrated pest management, Integrated weed management, Interdisciplinary research, Sustainable agriculture, Q-methodology, Weed science

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DEDICATION

I dedicate this dissertation to my Uncle John, who passed this spring, and to my daughter, Sofia, who we welcomed to this world on December 5, 2019. My uncle was a thoughtful and positive force in my life, who encouraged exploration and attention to detail. He was a patient teacher, a fellow lover of plants, and a constant source of encouragement. My daughter is a source of laughter and joy, who reminds me to stay present despite the challenges of life. I thank her for making me not take myself too seriously and remembering to enjoy the tranquil moments of family life.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The study of any subject begins by defining the focus of inquiry. In the case of agricultural weeds, this presents an interesting ontological question. *What exactly is a weed?* While weed science as a discipline relies on disciplines of biology, chemistry, ecology, and evolutionary biology a general definition of what makes a weed is not wholly derived from these. While suites of ecological traits have been ascribed to successful weed species, an all-encompassing definition has yet to be delineated (Bourgeois et al. 2019). Weeds are defined by their relationship to us, our human goals, and aesthetic preferences. In a certain sense, weeds could be considered social constructs, as their existence is predicated solely by our judgement and a definition of what makes a weed vary by individual and organization (Zimdahl, 2010). Over time, weeds have been defined in many ways by poets, scientists, and writers; the definition that speaks to me most defines a weed as “a plant out of place or growing where it is not wanted” (Blatchley, 1912; Merfield, 2022).

A weed can be a native plant intruding on a pasture, an exotic plant that reduces crop yield, or a cultivated crop that is impeding the growth of another cultivated crop, which highlights the context-dependent and anthropocentric nature of what a weed is (Booth et al. 2013). An official definition of a weed from the Weed Science Society of America is, “a plant that causes economic losses or ecological damage, creates health problems for humans or animals, or is undesirable where it is growing” (www.wssa.net/glossary). While a weed may indeed be a social construct, their presence and spread can be highly problematic to human activity. Weeds interfere with crops by competing for light, nutrients, and water (Zimdahl, 2004). Indeed, of all pest types, weeds are responsible for the largest potential percentage reductions in agronomic crop yield on a global basis (34%) (Oerke 2006). While this varies by crop type, geography, and management contexts, this suggests the relative importance of weed management and its effects on productivity, human nutrition, and farmer economic livelihoods.

Accordingly, for as long as agriculture has been practiced humans have devised ways of removing weeds from crop fields (Staver, 2001). For the bulk of agricultural history this has predominantly included physical removal of weeds with hands and tools and the use of cultural practices such as crop rotation (Staver, 2001). Towards the end of the 19th century, synthetic herbicide was used to manage weeds for the first time, presenting a novel method of management (Staver, 2001). However, given concentration and toxicity issues, application rates were incredibly high and often deleterious to crop plants, weeds, and humans alike (Clay, 2021). The management of agricultural weeds was truly revolutionized during the late 1940s and early 1950s with the discovery and adoption of synthetic herbicide that could be applied at lower relative rates and with some crop selectivity (Staver, 2001; Zimdahl, 2010; Clay, 2021).

Weed management and science from this period until the early 1980s has been dominated by the research and discovery of herbicide active ingredients, in addition to the development of associated technologies (Zimdahl, 2010). Considering herbicide development and use alone, the almost 50-year period between 1945 and 1995 represents a “golden age” in the discovery novel herbicide chemistries, and an almost total dominance as a primary means of controlling weeds in agricultural systems (Zimdahl, 2010). While highly effective, the use of herbicide constitutes an extremely strong selection pressure and when used repeatedly leads to the selection of herbicide resistant weeds (Zimdahl, 2010). This was predicted by plant biologist John Harper in 1956 and verified one year later with weeds in a pineapple plantation in Hawaii that were repeatedly exposed to the same herbicide chemistry (Harper, 1956; Hilton, 1957). Since the 1950s, there have been 521 unique cases of herbicide resistance comprising 23 of 26 herbicide sites of action (SOA) (Heap, 2022).

Within the Southeast region of the US, no weed has received more attention in the last 20 years than Palmer amaranth (*Amaranthus palmeri* S Watson), primarily due to the management challenges associated with herbicide resistance. Palmer amaranth is an annual forb, native to the Southwest, US (Ward et al. 2013). Biological characteristics such as dioeciousness and a C4 photosynthetic pathway allow for the maintenance of large genetic diversity and relative growth and resource use efficiency rates that far exceed many crop species (Bravo et al. 2017, 2018, Roberts and Florentine 2021, Ward et al. 2013). This is coupled with high morphological plasticity and reproductive potential; female plants can produce greater than one million seeds per plant (Ward et al. 2013). Palmer amaranth’s unique genetic, morphological, photosynthetic, and reproductive characteristics make it highly competitive relative to many crop species and extremely difficult to eradicate once even a few plants have been established and allowed to produce seed (Ward et al. 2013;).

Despite these myriad advantages, Palmer amaranth was not a weed of major concern until the widespread use of herbicide resistance cotton varieties in the mid-1990s engineered with resistance to the herbicide glyphosate (Webster and Sosnoskie 2010). The deployment of this technological package within the region was associated with a reduction in the diversity of herbicide SOA (Kniss 2018). Because cotton is an economically important crop in the region, a high prevalence of monocropping coupled with repeated use of few or one herbicide SOA led to the selection of glyphosate resistant Palmer amaranth, which came to occupy and ecological niche that had no existed prior (Culpepper 2006, Webster and Sosnoskie 2010). The economic impact of Palmer amaranth to cotton in the state of Georgia cannot be overstated as both yield decreases (due to weed-crop competition) and cost increases (due to costs associated with hand weeding and tillage to physically remove resistant weeds) led to a period of intense hardship for farmers in the Southeast (Price et al. 2011, Sosnoskie and Culpepper 2014).

Reducing the selection pressure of herbicides or increasing their efficacy is essential to ongoing weed management efforts for both Palmer amaranth and other species (Hand et al. 2021, Menalled et al. 2016, Neve et al. 2011, Wallace et al. 2019). The use of varied management practices that rely on cultural and biological approaches in addition to chemical ones is formally known as integrated weed management (IWM). IWM emerged in the late 1970s in response to increasing challenges with herbicide resistant weeds, farmer economic livelihoods, and environmental quality issues (Zimdahl, 2010).

Within industrialized row crop systems in the US, the cultural practice that has received the most amount of research attention, funding, and farmer interest as part of an IWM system is the use of cover crops (CC) (Teasdale, 2018). CC are annual species of grasses and forbs that are established after cash crop planting in the fall, and terminated prior to cash crop planting in the spring. Within no-till systems this results in a layer of vegetative biomass that remains on the soil surface. CC appear to suppress weeds through a variety of mechanisms including acting as a physical barrier to seedling emergence, altering the quantity and quality of light required for seed germination, and changing the soil environment through the introduction of allelochemicals and by lowering relative soil temperature (Teasdale, 2018). Numerous studies have demonstrated the weed suppressive ability of CC, including several meta-analyses (Nichols et al. 2020, Osipitan 2018, Osipitan et al. 2019). Generally speaking, CC efficacy in suppressing weeds is most tied to the quantity of biomass that is generated and left on the soil surface as residue (Nichols et al. 2020, Osipitan 2018, Osipitan et al. 2019).

While less studied, living mulches may provide another management practice to augment IWM systems. Unlike CC, living mulches remain alive synchronously to cash crop growth (Hartwig and Ammon 2002, Mohammadi 2012, Paine and Harrison 1993, Westbrook et al. 2022). A planting row is established within a living mulch to aid in cash crop establishment. From a weed management standpoint, this means that the inter-row area is occupied by a living plant, which may further optimize some of the weed suppression mechanisms mentioned above (Mohammadi 2012, Westbrook et al. 2022). Living mulch species may be annual or perennial, but recent work in Georgia has experiment with a white clover ecotype called Durana®. Agronomic studies have shown it to be a suitable species for use in corn production systems in Georgia specifically (Andrews et al. 2018, Sanders et al. 2017, 2018). However, research into the contribution of living mulches to weed suppression in the agronomic cropping systems of the Southeast is limited.

More so even, despite documented benefits of CC, their actual implementation remains limited, and we could find no data on adoption rates of living mulches in the Southeast or US at large (Wallander et al., 2021). Reasons for limited CC adoption are numerous and context-dependent, but salient themes include a perception of agronomic and economic risk associated with the implementation of a novel practice, particularly in the absence of economic incentives. Social science research examining both CC adoption broadly, and IWM adoption specifically, support this overall finding (Liebman et al. 2016, Owen et al. 2015, Roesch-McNally et al. 2018, Thompson et al. 2021). For IWM practices specifically, social science research conducted within the last 10 to 15 years has increasingly focused on what factors influence the perceptions of farmers (Ervin and Jussaume, 2014). While farmers represent the most proximate stewards of herbicides and weed management systems, university extension agents, as well as industry representatives and agrichemical consultants are integral parts of the “social ecosystem” that shapes proximate weed management practices and downstream consequences.

The necessity of capturing the perceptions of all stakeholders within this social ecosystem led us to the use of Q-methodology (QM). QM was developed by psychologist William Stephenson in the 1930s (Brown, 2019). QM joins qualitative and quantitative methodological tools to identify and describe different viewpoints about a subject or question of interest. QM has been increasingly used in the field of rural sociology for its ability to, “study people’s own perspectives, meanings and opinions” (Previte et al. 2007). Given the methodological goals of identifying and describing human subjectivity, Q has been used extensively in the fields of agriculture, and natural resource use. Recent applications have looked at values of progressive cattle farmers in Brazil (Pereira et al. 2016), farmer decision-making in rice systems in Laos (Alexander et al. 2018), and pesticide use and risk for agricultural workers in Washington State (Lehrer and Sneegas 2018). Given its applicability in the contexts described above, we felt that QM presented an interesting and useful methodological fit for our questions around the use of IWM within agronomic cropping systems and stakeholder perceptions therein.

Collectively, the dissertation document is an interdisciplinary work intended to use methodological and epistemological tools and insights drawn from both biophysical and social science disciplines. Furthermore, both quantitative and qualitative methodological approaches were implemented in the works presented in this document and are considered as valid sources of information. The first chapter of the dissertation is the introduction and literature review presented here. The second chapter of the dissertation is a meta-analysis that examines the effects of annual cover crops on weed suppression and crop production in the Southeast US. The third chapter examines the effects of both annual cover crop and living mulch systems on Palmer amaranth population dynamics using a 2-year field study based in Watkinsville, GA at the J. Phil Campbell Research and Education Center. The fourth chapter details the use of QM in identifying and describing stakeholder perceptions on the management of Palmer amaranth in the Georgia Coastal Plain. The fifth chapter entails an overarching discussion of the work, synthesizing its outcomes, as well as providing suggestions for further research and action relative to IWM practices.

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CHAPTER 2

DO COVER CROPS SUPPRESS WEEDS IN THE SOUTHEAST US? A META-ANALYSIS [1]

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[1] Weisberger, D., Bastos, L.M., Sykes, V., and N. T. Basinger. To be submitted to *Weed Science*.

Abstract

Cover crops (CC) have shown great potential in suppressing many annual weeds within agronomic cropping systems across the US. However, the weed suppressive potential of CC may be moderated by environmental and management factors that are specific to certain geographic areas and their associated characteristics. This may be particularly true within the Southeast (SE) region of the US where higher mean annual temperature and precipitation generate favorable conditions for both CC and weed growth. To understand the effects of this regional context on CC and weeds, we performed a meta-analysis examining paired comparisons of weed biomass and/or weed density under CC and bare ground conditions from studies conducted within the SE. We identified and extracted relevant data from 28 journal articles in which weed biomass and/or weed density were measured. We also extracted cash crop yield data from articles if they were provided. Fourteen studies provided 142 comparisons for weed biomass, 23 studies provided 139 comparisons for weed density, and 22 studies, pooled over both weed response variables, provided 144 comparisons for cash crop yield. We found that CC had a significant negative effect on weed density ($p = 0.0016$), but had no effect on either weed biomass ($p = 0.16$) or cash crop yield ($p = 0.88$). The mean relative reduction in weed density under CC was 44 percent. Subsequent analyses indicated that CC biomass was the key factor associated with this reduction. Weed density suppression was linearly related to CC biomass; a 50 percent decrease in weed density was associated with 6.6 Mg ha^{-1} of CC biomass. Other edaphic, geographic, and management factors had no bearing on this suppressive effect. This highlights the importance of generating adequate CC biomass and the potential for CC to reduce weed density over diverse soil, climate, and farm management conditions.

Introduction

The Southeast (SE) region of the US is a geographically and edaphically diverse region typified by high relative temperatures and humidity coupled with mild winter conditions that are favorable to plant growth (Konrad and Fuhrmann, 2013). From an agronomic perspective, the SE region comprises widely grown field crops such as corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.), in addition to those that are predominantly grown in this region, such as cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) (Asseng et al., 2013; Knox et al., 2014). Given the biophysical context of the region, weeds are ubiquitous, and infestations can be severe. Weed management of agronomic crops in the SE is based almost exclusively on herbicide-centric approaches (Norsworthy et al. 2012, Price et al. 2016). While herbicides are a highly effective management tool, their efficacy is continually threatened by the potential for selecting herbicide-resistant weed biotypes (Menalled et al. 2016, Neve et al. 2014). The likelihood of this phenomena is proportional to weed population size and the selection pressure imposed by herbicide (Menalled et al. 2016, Neve et al. 2014). Using ancillary practices that both limit selection pressure and maintain small population size is essential to the ongoing challenge of weed management in the SE region (Hand et al. 2021, Norsworthy et al. 2012, Price et al. 2016). The deliberate use of varied practices that differ in the selection pressure that they impose on weeds is a central tenet of integrated weed management (IWM) approaches (Harker 2013, Menalled et al. 2016, Neve et al. 2014).

One such practice, the use of cover crops (CC), has been studied extensively as a cultural tactic to limit weed germination, emergence, and growth (Teasdale, 2018). CC have been shown to alter these processes by altering light quantity and quality, providing a physical barrier, and increasing seed predation among others (Teasdale et al., 2018). CC use has steadily increased in the SE region, particularly in the last 10-15 years (Wallander et al., 2021). While much of this recent uptick in adoption may be related to potential CC-based improvements around soil erosion and moisture retention, research has shown that the weed-suppression related benefits of this practice are an important feature of sustained farmer CC use (Hancock et al., 2020). This has become increasingly true in the SE region given the ongoing difficulty in managing several highly problematic weed species that have developed resistance to many commonly used herbicide sites of action (SOA). However, understanding if CC provide weed-suppression benefits and what key factors either attenuate or amplify their ability to do so is critical to their success and continued adoption as a weed management practice.

Both global and regional meta-analyses on the effect of CC on weeds has supported their potential as a weed management practice, but management factors differed around factors of management and study scope of inference (Nichols et al. 2020, Osipitan 2018, Osipitan et al. 2019). For example, Osipitan et al. (2019) found little to no difference in the suppressive ability of different CC species when looking at studies on a global basis across both agronomic and horticultural production systems, while Nichols et al. (2020) found that only grass CC species had a significant effect on the reduction of weed biomass within agronomic cropping systems of the US Midwest.

Given the potential for context-dependencies, we were interested in understanding how well CC suppress weeds within agronomic cropping systems of the SE, focusing on weed biomass and weed density as response variables. We conducted a meta-analysis to explore the effects of CC on weeds in the SE region and the moderating effect of a variety of factors on potential CC-based weed suppression. Specifically, we sought to answer the following questions: (i) Do CCs suppress weed biomass and/or weed density? (ii) What is the magnitude of this effect? (iii) Under which contexts is this effect greatest? (iv) To what extent do trade-offs exist between weed suppression and cash crop yield?

Materials and methods

Literature search and data extraction

A systematic search of the literature was conducted using Web of Science Core Collection, CAB Abstracts, and BIOSIS databases. The search was conducted from June through August of 2020 using the following Boolean string: ("weed management" OR "weed control" OR "weed science" OR "weed suppression") AND "cover crop" OR "catch crop" OR "green manure”. An initial selection criterion required that all literature be peer-reviewed and that studies were conducted in one of the nine USDA-ARS SE region states within the contiguous US; this includes Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee (https://www.ars.usda.gov/southeast-area). Further filtering was based on identifying journal articles that measured the response variable weed biomass (WBIO) or weed density (WDEN) and measured said response variables in the same crop, at the same time point, with all management activities being identical save for the presence of a fall-planted CC. The specifics of the literature search are documented in a PRISMA flow chart (Appendix A).

From selected publications, paired comparisons of WBIO or WDEN were extracted from tables and/or figures within our selected journal articles. When data were presented solely in figure-format, the GetData graph digitizer (http://getdata-graph-digitizer. com/) was used to extract relevant data. For WDEN, if measurements were taken at multiple time points in a season, we either extracted data from the final WDEN measurement, if that value represented a cumulative seasonal total, or summed all values to generate a value for the cumulative seasonal total. For each comparison, we also extracted data for cash crop yield (CY), if this data was provided. Relevant study information was extracted and assessed as potential moderator variables. Examples of relevant information include study duration and experimental design, geographical and pedological specifics, cover crop management details, and the type of weeds present in a study.

Data analysis

The response variables WBIO, WDEN, and CY were transformed into the natural log of the ratio between response value with CC (numerator) and response value without CC (denominator); i.e., the log response ratio (LRR). This is a common practice to deal with the high degree of variance from studies give the spatial and temporal differences across selected publications (Philibert et al, 2012). In 11 comparisons, either the treatment or control variable value was zero and comparisons were removed prior to analysis. Previous work has shown that adding an arbitrary small value to both numerator and denominator in order to compute an LRR can lead to unrealistic values, and even change values from negative to positive (Verret et al. 2017, Weisberger et al. 2019). Also, fewer than 20 percent of all studies reported measures of intra-study variance (e.g., standard deviation or standard error). Based on this, each study was weighted using a non-parametric method based on sample size (Lajeunesse, 2013). The overall effect, of a CC relative to no CC, on each of the three response variables (LRR_{WBIO}, LRR_{WDEN}, LRR_{CY}) was assessed using random-effect models with publication as the random effect, testing whether the overall mean was different than zero.

Conditional inference trees (CIT) were used as an analytical approach to explore potential interactions among our dependent variables. CIT has been increasingly used in agronomic studies where identifying interactions among multiple independent variables has been used to understand management effects on productivity and environmental quality (Lollato et al., 2019; Bastos et al., 2021; Jaenisch et al., 2021; Vann et al., 2021). CIT have also been used in the context of meta-analyses, where they are a particularly good fit when dealing with unbalanced datasets, missing data, and both categorical and continuous variables (Philibert et al. 2012, Pittelkow et al. 2015). CIT do not rely on parametric statistical assumptions, limiting bias and overfitting issues that are common in other regression tree approaches, and were specifically developed to identify interactions within complex datasets to facilitate interpretation (Hothorn et al., 2006; Nembrini, 2019). Operationally, CIT uses an algorithm that implements multiple null hypothesis tests between a chosen response variable (e.g., LRR_{WBIO}, LRR_{WDEN}, LRR_{CY}) and each level of an independent variable (e.g., soil type or CC species). It then selects the independent variable with the strongest association to the response variable, determined by the lowest p-value, and performs a binary split in the data set at this juncture. This process is repeated recursively, resulting in a "tree" with multiple intermediate and terminal nodes (Mourtzinis et al., 2018).

The significance of our overall model of the CC effect on our three response variables guided the implementation of CIT. Consequently, a significant effect of CC occurred solely with respect to weed density (LRR_{WDEN}) and CIT analysis was performed only on this specific response variable. Tree terminal node means were further compared using a mixed-effect model with LRR_{WDEN} as the response variable and terminal node membership (fixed-effect) and publication (random effect) as the explanatory variables. Based on insights from Vann et al.

(2021), in addition to p-value, ≥ 20% of total observations were present at intermediate nodes, and ≥ 5% of total observations at terminal nodes to ensure adequate power (n = 139).

CIT identified cover crop biomass as an important moderator of LRR_{WDEN}, thus we further explored this relationship by regressing LRR_{WDEN} against cover crop biomass. A variety of linear and non-linear relationships were fit to this relationship, and Aikaike and Bayesian information criteria values were used to determine the best fit for the selection of a specific model **(**Müller et al., 2013). Lastly, all paired values of LRR_{WBIO} or LRR_{WDEN} and LRR_{CY} were categorized as win (cover crop either decreased weed density/biomass or increased grain yield) or lose (cover crop either increased weed density/biomass or decreased grain yield) creating four quadrants. The number of observations in each win-lose quadrant was counted to assess the frequency of the concurrent effects of a CC on weed suppression and crop yield.

Data wrangling, statistical analysis, and visualization were performed in R software version 3.6.2 (R Core Team, 2016). Random- and mixed-effect models were run using the "lmer" function from the lme4 package (Bates et al., 2015). Fixed-effect models were run using the "lm" function from the stats package. Conditional inference tree was run using the "ctree" function from the partykit package (Hothorn et al., 2006). Statistical significance of all model results was evaluated using alpha = 0.10.

Results and discussion

Literature search

After removal of duplicates and application of the filtering criteria described above, 219 abstracts were screened, leading to the selection of 68 peer-reviewed publications that met our initial selection criteria. These were read, and 28 papers were identified based on meeting all criteria including proper comparisons of treatment (CC) and control (bare ground) groups, and used for data extraction and analysis (Appendix B). This generated a total of 281 paired comparisons. 142 comparisons were extracted from 14 papers for WBIO, 139 comparisons from 23 papers for WDEN. While recent studies have looked at CC effects on weeds at a global scale (Osipitan 2018, Osipitan et al. 2019) (Osipitan et al., 2018, 2019) and in cotton production systems specifically (Toler et al. 2019) (Toler et al., 2019), the results of our literature search indicated the presence of only four and five shared publications, respectively. This limited amount of overlap highlights the novelty of our dataset and analyses. All 15 categorical and continuous moderator variables, with associated sample size, moderator levels, and summary statistics are presented in Table 2.1. All 28 studies and the associated LRR are presented in Table 2.2. Studies represented all states from the USDA-ARS Southeast region, except for Louisiana. Studies varied in the number of comparisons conducted at each site, with most sites associated with between one and five comparisons used in our analysis (Fig. 2.1).

Overall effects and the role of CC biomass

CC reduced WDEN ($p = 0.00023$), but had no significant effect on WBIO (21% reduction, $p = 0.16$) (Fig. 2.2). Over all studies, CC reduced WDEN by an average of 44% (Fig. 2.2). The results of CIT for WDEN returned five nodes, including three terminal nodes associated with the LRR of this response variable (Fig. 2.3). An initial split in the dataset occurred as a function of publication date, where data were aggregated into comparisons that occurred before and after 2002 (Fig. 2.3). A second split resulted in an intermediate node that split all comparisons after 2002 based on a CC biomass threshold of 3.3 Mg ha^{-1} (Fig. 2.3). Accordingly, mean separation among LRR_{WDEN} values at the three terminal nodes indicated significantly different values (Node 2 = LRR_{WDEN} values from prior to 2002, node 4 = LRR_{WDEN}

values from after 2002 having less than 3.3 Mg ha^{-1} CC biomass, and node 5 = LRR$_{\mathrm{WDEN}}$ values from after 2002 having greater than 3.3 Mg ha^{-1} CC biomass, Fig. 2.3). These terminal nodes were associated with LRR$_{\mathrm{WDEN}}$ of 0.36, -0.53, and -0.87, which are associated with a 34% increase, 42 and 58% decreased LRR$_{\mathrm{WDEN}}$, respectively (Fig. 2.3). These results indicate that for studies conducted after 2002, CC biomass was the fundamental moderator associated with decreased WDEN; increased biomass above a 3.3 Mg ha^{-1} threshold was associated with the greatest suppressive effect on this response variable.

Our results indicate that CC biomass was the key driver in reducing WDEN. CC biomass was linearly correlated with increased suppression of WDEN (decreased LRR$_{\mathrm{WDEN}}$). Results of regression analysis found that a 50% relative reduction in WDEN was associated with 6.6 Mg ha^{-1} of CC biomass (Fig. 2.4). Analyses did not indicate the importance of any additional moderators, suggesting that the relative suppressive effect of CC on WDEN is present across a wide range of edaphic conditions (e.g., soil texture and pH) and management choices (e.g., CC and cash crop species selection, tillage system, and herbicide use). Both recent meta-analyses and experimental work have come to similar conclusions, particularly with respect to the effect of CC biomass (Baraibar et al. 2018, MacLaren et al. 2019, Nichols et al. 2020, Osipitan 2018, Osipitan et al. 2019). Nichols et al. (2020), who conducted an analogous meta-analysis of CC effects on weeds in the US Midwest, also found that the relative effect of CC biomass was an important moderator of weed suppression, and this suppressive effect was unaffected by varied geographic environments, tillage and crop planting decisions, and herbicide use as well.

However, the results of Nichols et al. (2020) differed from ours in two important ways. Firstly, within the Midwest context, CC exhibited a suppressive effect on WBIO and not WDEN. Furthermore, CC type was an important moderator of this effect. That work found that grass CC (predominantly cereal rye) was associated with a significant mean WBIO reduction of 68%, while the 33% reduction associated with other CC types was not significant. In that study the quantity of CC biomass associated with a 75% reduction of WBIO was 5 Mg ha^{-1}. Conversely, our results only demonstrate a suppressive effect of CC biomass on WDEN; and neither CC species nor type were significant moderators. While the response variables were different across meta-analyses, these contrasting findings point to the importance of factors, such as heat unit accumulation, that regulate CC biomass accumulation. Both field studies and modelling work have substantiated the effect of heat unit accumulation on CC biomass and its potential impact on weeds (Baraibar et al., 2018; Nichols et al., 2020). To further quantify these regional differences, the maximum values for CC biomass in our study exceeded those recorded in Nichols et al., 2020 by approximately 3.5 Mg ha^{-1}, highlighting the favorable climatic conditions of the SE to generate substantial biomass irrespective of CC type of species.

The key determinants in generating sufficient CC biomass to suppress weeds are planting and termination dates; these two “windows” determine the cumulative amount of heat units to which a CC is exposed (Price et al. 2016, Nichols et al. 2020). A study conducted across sites in AL and FL examining the effects of four planting and four termination dates found that CC biomass values for cereal rye and crimson clover, unsurprisingly, were greatest at the earliest planting date and latest termination date (i.e., the largest possible growth window). Conversely, CC biomass values for cereal rye and crimson clover were reduced by factors of eight and ten, respectively, when planting was latest and termination earliest (i.e., the smallest possible growth window) (Price et al. 2016). While heat unit accumulation is clearly the determinant in generating adequate CC biomass, this can be highly constrained by cash crop production practices as farmers are incentivized to increase cash crop yield as much as possible. This often entails the use of crop varieties that optimize heat units and solar radiation. Practically speaking, this means that planting dates have become earlier and harvest dates later over time, which has become increasingly possible because of climate change (Knox et al. 2014, Cammarano and Tian, 2018).

Due to this agronomic and economic reality, research has increasingly explored ways to establish cover crops earlier and terminate them later without requiring wholesale changes in the adoption of shorter-season cash crop varieties. Establishment methods have made use of aerial CC seeding via planes and helicopters, as well as ground driven equipment such as “highboy” applicators that do not damage the growing crop (Bergtold et al. 2019). However, these methods require higher CC seeding rates, due to greater seed and seedling losses (Bergtold et al. 2019). Additionally, the use of drill-interseeding has been explored to combine earlier seeding (during cash crop vegetation development) and the benefits of a drill, namely good seed-soil contact (Curran et al. 2018). Findings on CC biomass via drill interseeding have been mixed, and appear highly contingent on in-season weather patterns (Moore and Mirsky, 2020, Stanton and Haramoto, 2021). Drill interseeding also requires specialized equipment and may impact in-season herbicide management (Curran et al., 2018; Stanton and Haramoto, 2021). Later termination of CC has also been researched, and one method in particular, “planting green,” has been receiving increasing research attention following from farmer experimentation (Reed et al. 2019, Quinn et al. 2021, Grint et al. 2022). Planting green entails planting a cash crop into a living CC, and terminating the CC at the time of planting or shortly after to optimize the benefits of the CC (Reed et al., 2021). Research in Kentucky demonstrated that post-plant CC termination of cereal rye, associated with a 21-day difference from standard CC termination practices, resulted in approximately twice as much CC biomass (Quinn et al., 2021). The relative merits and trade-offs of these warrant further investigation particularly within the SE states upon which our analyses are based.

While greater CC biomass at planting is more effective at suppressing the germination and emergence of weed seedlings, particularly during the earlier part of the growing season, the ability of CC biomass to suppress the growth and development of WBIO in the SE may be constrained by the very same factors that make it successful in reducing WDEN. For example, faster accumulation of heat units and high relative humidity levels, like those of the SE, are equated with expedited rates of CC biomass decomposition, as well as weed growth and development (Reinhardt Piskackova et al. 2021, Thapa et al. 2022). Simply put, decreased CC biomass covering the soil over the course of the season coupled with a favorable environment for WBIO accumulation suggest a successful trajectory for any weeds that evade chemical or physical control. This is compounded by the fact that many of the most prevalent weed species in agronomic cropping systems of the SE are those that possess a C4 photosynthetic pathway providing them a relative advantage to most crops in the region. Salient examples include annual and perennial grasses such as broadleaf signalgrass (*Urochloa platyphylla* (Nash) R.D. Webster) and Johnson grass (*Sorghum halepense* (L.) Pers.), in addition to the broadleaf Palmer amaranth (*Amaranthus palmeri* S. Wats.), as well as nutsedge species (*Cyperus* spp.) (Webster et al. 2012, Ward et al. 2013, Sage, 2016, Rojas-Sandoval, 2019, Travlos et al., 2019).

Given this fact, finding ways of reducing WDEN levels even further and dealing with escapes is paramount. Coupling CC use with herbicide best management practices is an essential part of this equation; particularly the use of overlapping residual chemistries, rotation of diverse herbicide SOA, and the use of post-direct applications (Norsworthy et al. 2012). While we did not find a synergistic effect of CC and herbicide in our study, a reduction of WDEN by almost

50% relative to bare ground is a positive finding, but highlights room for improvement. While the study of CC-herbicide interactions is not new (Teasdale 1996), more recent work has elucidated the mechanisms behind how CC and herbicide may synergistically limit weed seed germination and seedling survival (Bunchek et al. 2020, Wallace et al. 2019).

Additionally, studies within the SE have shown that CC growth and biomass accumulation is not limited by many commonly-used residual herbicides suggesting that CC integration as an IWM tactic is not impeded by the current spectrum of active ingredients (Palhano et al. 2018) (Palhano et al. 2018, Rector et al., 2019). Further integration of novel management practices may augment CC-herbicide synergies. One recent example involves the idea of "weed priming" (Oliveira et al. 2020). Authors from that study hypothesized that the use of plant hormones could either homogenize weed seed germination patterns or induce higher levels of dormancy. In either case, coupled with pre-emergent herbicide and CC-use, this could be a highly effective practice to both increase the efficacy of pre-emergent herbicide and potentially limit selection pressure by minimizing the heavy reliance on post-emergent herbicide. Empirical work is needed to substantiate these hypotheses, but this presents a creative approach to CC-based IWM.

Crop yield and weed management tradeoffs

Crop yield comparisons were pooled over our WBIO and WDEN comparisons, resulting in 144 comparisons over 22 publications. Our results indicated that LRR_{CY} was not significantly different from zero (8% increase, $p = 0.88$) (Fig. 2.2). While CC-driven gains in soil conservation and moisture retention have been seen across varied sites within the SE, improvements to these properties may only improve crop yields in growing seasons when precipitation amounts may be limited or with the inclusion of a legume CC (Farmaha et al., 2022). LRR values for crop yield and both weed responses were visualized together to quantify the number of comparisons where both crop yield responses were above zero, and weed responses were below zero, leading to the characterization of “win” and “loss” scenarios (Fig. 2.5). The best possible outcome for increased yield and reduced weeds (“win-win,” W-W) occurred over 38% of comparisons. These data also indicate that while 70% of all weed response comparisons were less than zero, only 47% of yield comparisons were above zero (Fig 2.5). This may be an artifact of the studies included in our analyses, as most were designed to evaluate the suppressive effect of CC on weeds, but it may also suggest trade-offs around optimizing crop yield under CC. Additionally, because crop yield response from comparisons were taken from broad temporal, geographic and management gradients, this may mask benefits accrued during years of precipitation deficit or nitrogen limitation.

Conclusion

Given the challenges of weed management in the SE region, CC have an important role to play in IWM systems. While our results strongly highlight the role of CC biomass in reducing WDEN, we recognize the challenge of achieving certain thresholds given current agronomic and economic objectives and concerns stemming from farmers themselves. Increased interest and study around CC establishment and termination options show promise for balancing crop production and weed suppression goals. This interest and excitement appear consistent across industry, farmer, and university stakeholders - suggesting that balancing multiple objectives in CC-based systems is a high priority that is drawing on a diversity of experience and knowledge. However, we end by cautioning that without proper support in the form of education and policy to both increase adoption and ensure best management practices, these collaborations and shared efforts will be impeded.

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Table 2.1. List of moderators, levels, associated sample sizes and summary statistics for categorical and continuous independent variables across all 28 studies.

Categorical moderator variable (sample size, N)	**Level (sample size, n)**
CC species (N = 241)	Austrian winter pea (n =2)
	Cahaba vetch (n = 1)
	Cereal rye (n = 112)
	Cereal rye + Austrian winter pea (n = 5)
	Cereal rye + cahaba vetch (n = 1)
	Cereal rye + crimson clover (n = 19)
	Cereal rye + hairy vetch (n = 5)
	Cereal rye + narrow-leaf lupine (n = 1)
	Crimson clover (n = 35)
	Hairy vetch (n = 28)
	Italian ryegrass (n = 3)
	Narrow-leaf lupin (n = 1)
	Oat (n = 3)
	Rapeseed (n = 1)
	Subterranean clover (n = 14)
	Triticale (n = 1)
	Wild radish (n = 1)
	Winter wheat (n = 5)
CC termination method (N = 238)	Herbicide (n = 146)
	Herbicide + mowing (n = 12)
	Herbicide + roller-crimping (n = 52)
	Mowing (n = 6)
	Roller-crimping (n = 17)
CC type (N = 241)	Brassica (n = 2)
	Grass (n = 127)
	Legume (n = 81)
	Mix (n = 31)
Crop species (N = 241)	Corn (n = 78)
	Cotton (n = 109)
	Peanut (n = 5)
	Soybean (n = 49)
Herbicide use (N = 238)	Herbicide not used (n = 68)
	Herbicide used (n = 170)
Location (state) (N = 281)	Alabama (n = 62)
	Arkansas (n = 27)
	Florida (n = 4)
	Georgia (n = 35)
	Mississippi (n = 43)
	North Carolina (n = 92)
	South Carolina (n = 12)
	Tennessee (n = 6)
Soil type (N = 217)	Clay (n = 12)
	Fine sand (n = 4)
	Loamy sand (n = 51)
	Sandy loam (n = 79)
	Silt loam (n = 58)
	Silty clay loam (n = 4)
	Silty loam (n = 9)
Tillage system (N = 220)	No-till (n = 146)
	Strip-till (n = 24)
	Tillage prior to CC establishment (n = 50)
Weed community composition (N = 241)	Community (> 1 species) (n = 149)
	Single species (n = 92)
Weed type (241)	Summer annual (n = 224)
	Summer annual + perennial (n = 17)
Continuous moderator variable (sample size, N)	**Range (median)**
Cover crop biomass (N = 186)	0 - 12.9 (3.7)
Cover crop seeding rate (kg ha^{-1}) (N = 265)	6 – 178 (80)
Soil OM% (N = 105)	0.4 – 2.0 (0.6)
Soil pH (N = 90)	5.5 - 6.9 (6.2)
Year of publication (N = 241)	1985-2019 (2011)

Table 2.2. List of publications and associated natural log response ratios (LRR) for weed biomass (WBIO), weed density (WDEN) and crop yield (CY).

Publication	LRR_{WBIO}	LRR_{WDEN}	LRR_{CY}
Aulakh et al., 2012		✓	✓
Aulakh et al., 2013		✓	✓
Brown and Whitwell, 1985		✓	✓
DeVore et al., 2012		✓	✓
DeVore et al., 2013		✓	✓
Hand et al., 2019		✓	✓
Koger et al., 2002	✓	✓	✓
Koger et al., 2005	✓	✓	✓
Lassiter et al., 2011		✓	
Malik et al., 2008		✓	✓
Norsworthy and Frederick, 2005	✓		✓
Norsworthy et al., 2016		✓	✓
Palhano et al., 2018		✓	✓
Price et al., 2012	✓	✓	✓
Price et al., 2016		✓	✓
Reddy and Koger, 2004	✓	✓	✓
Reddy et al., 2003	✓	✓	✓
Reddy, 2001	✓	✓	✓
Reddy, 2003	✓	✓	✓
Smith et al., 2011		✓	
Timper et al., 2018		✓	
Vann et al., 2018	✓		✓
Webster et al., 2013	✓	✓	✓
Well et al., 2013		✓	
Wells et al., 2016	✓		
Wiggins et al., 2017		✓	
Yennish et al., 1996	✓		✓
Zotarelli et al., 2009	✓		✓

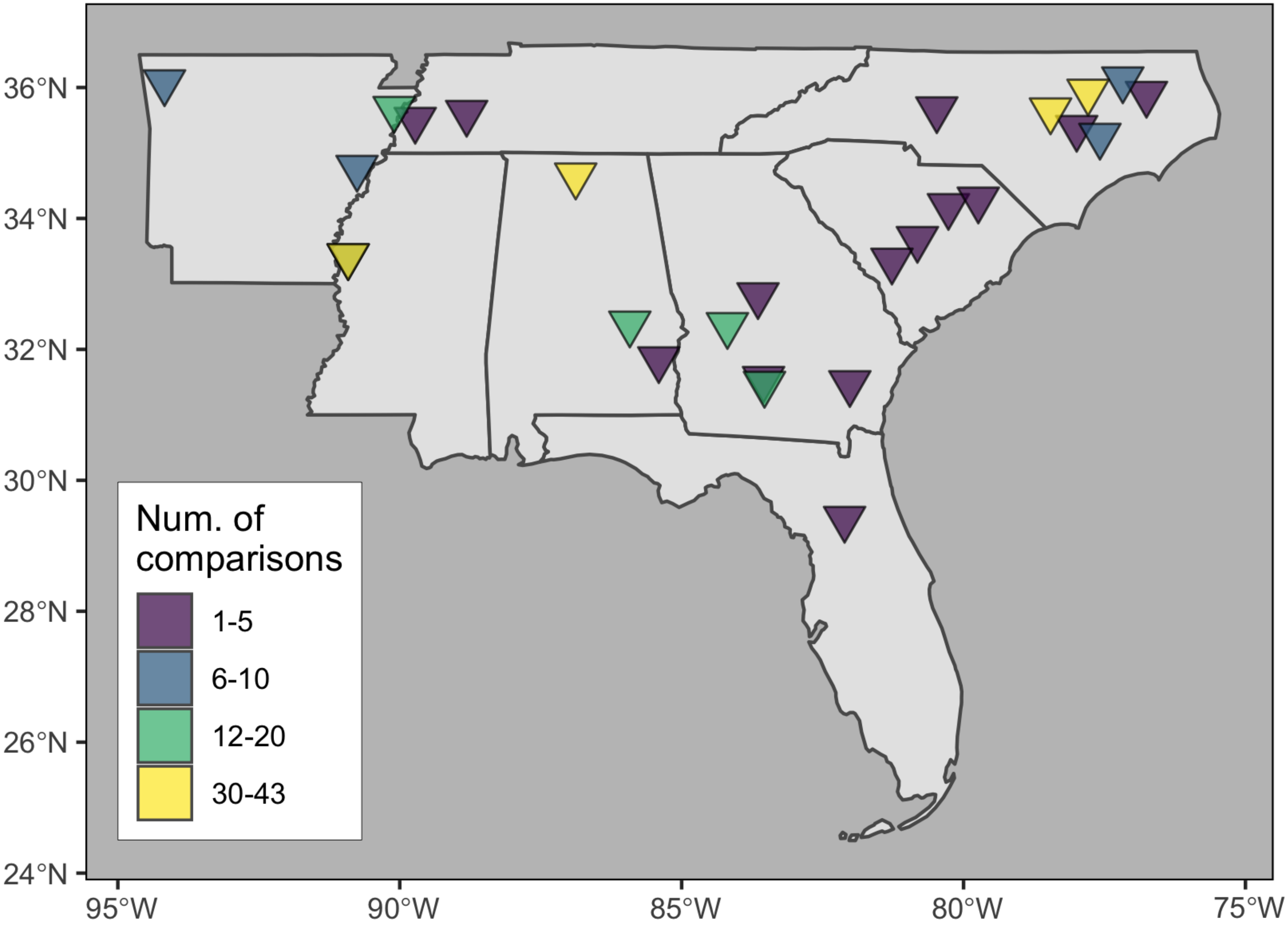
Figure 2.1. Map of study locations used in meta-analysis. Triangles are colored to correlate to the number of paired comparisons from each location.

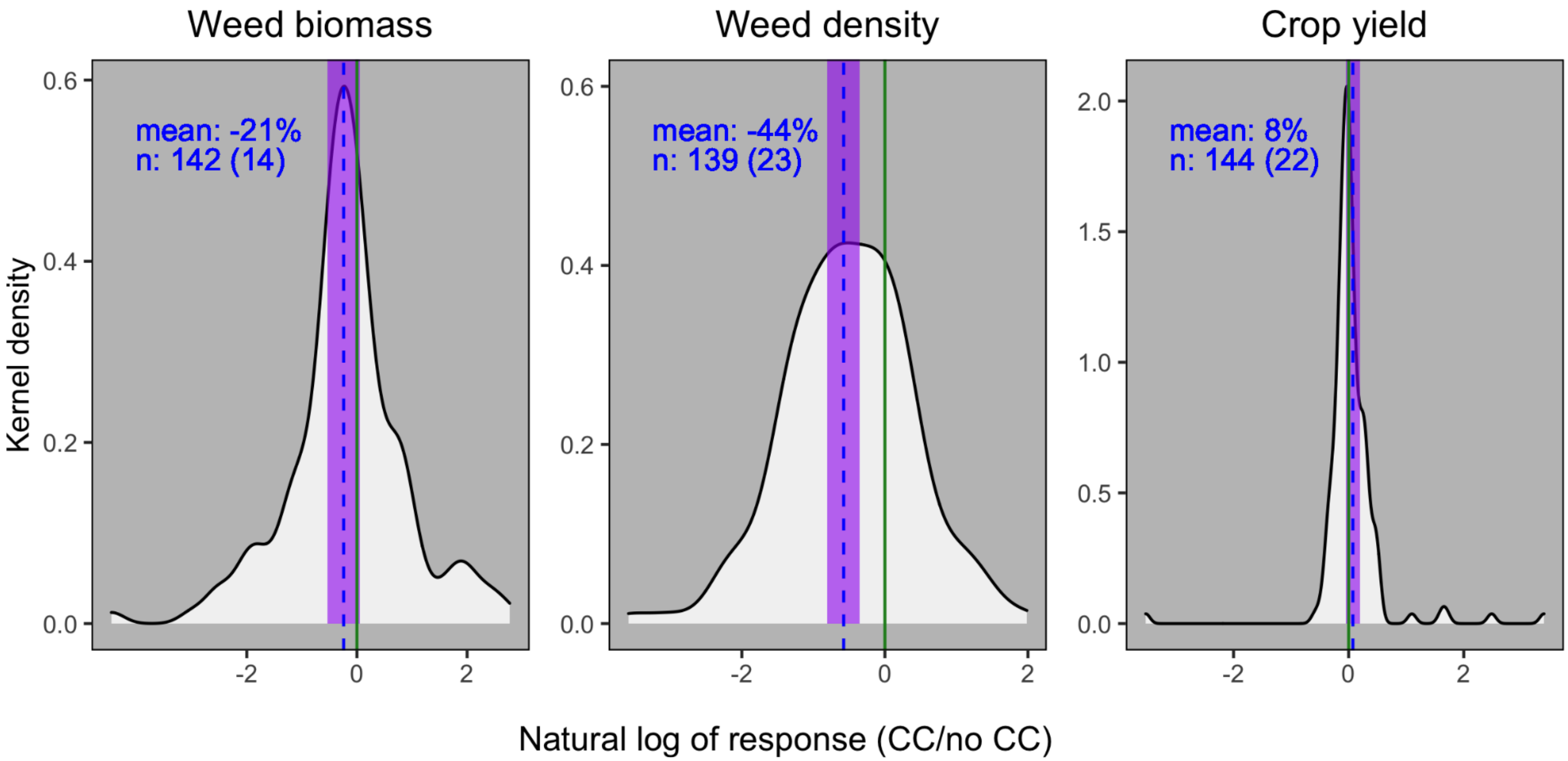
Figure 2.2. Overall mean effect of CC on weed biomass, weed density, and crop yield. The blue dotted line, purple bar and green solid line represent the mean response, 95% confidence interval and no response, respectively. Statistical difference (mean response is significantly different than zero) was assessed with $\alpha = 0.10$.

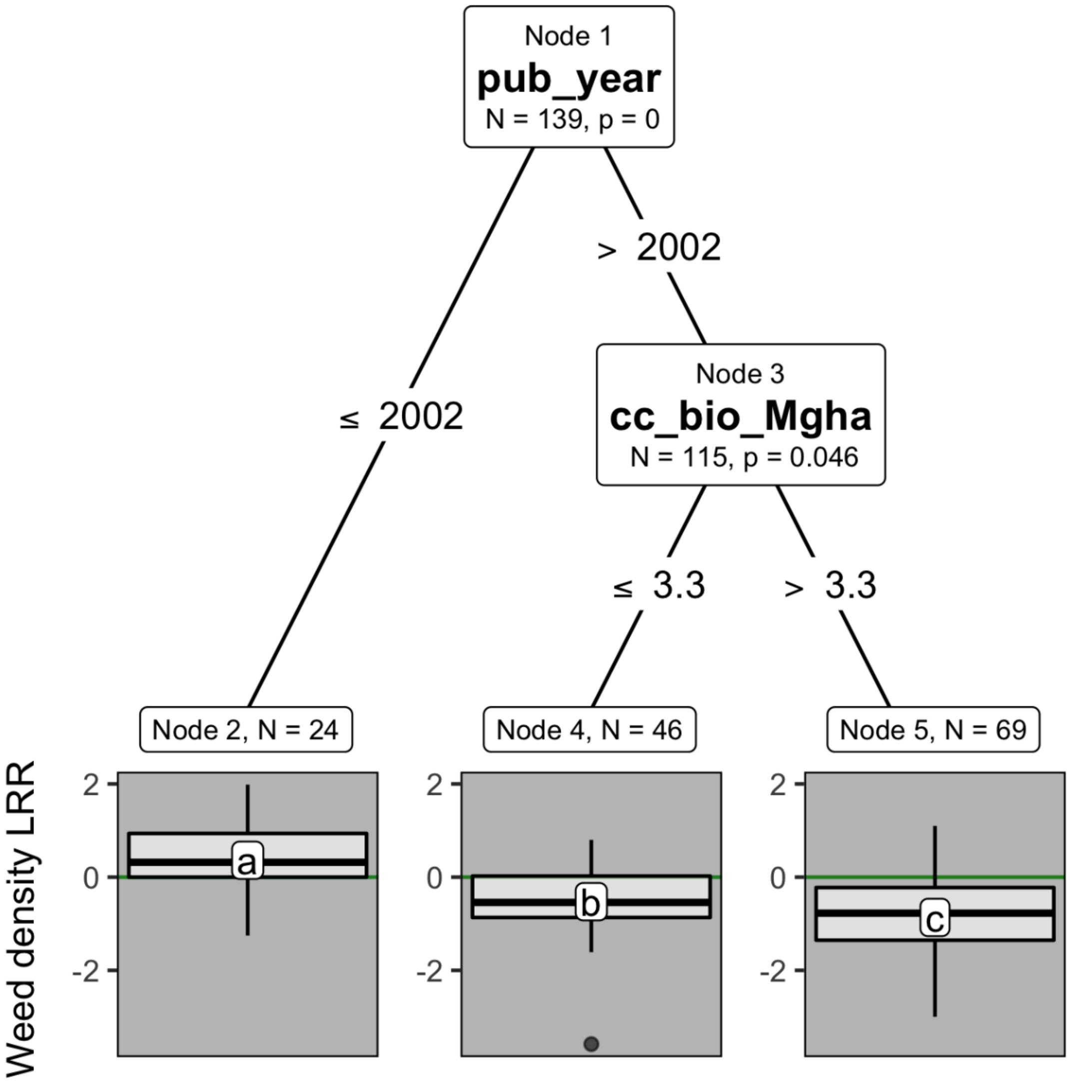
Figure 2.3. Conditional inference tree for LRR_{WDEN}. Mean response values followed by the same letter are not significantly different ($\alpha = 0.10$).

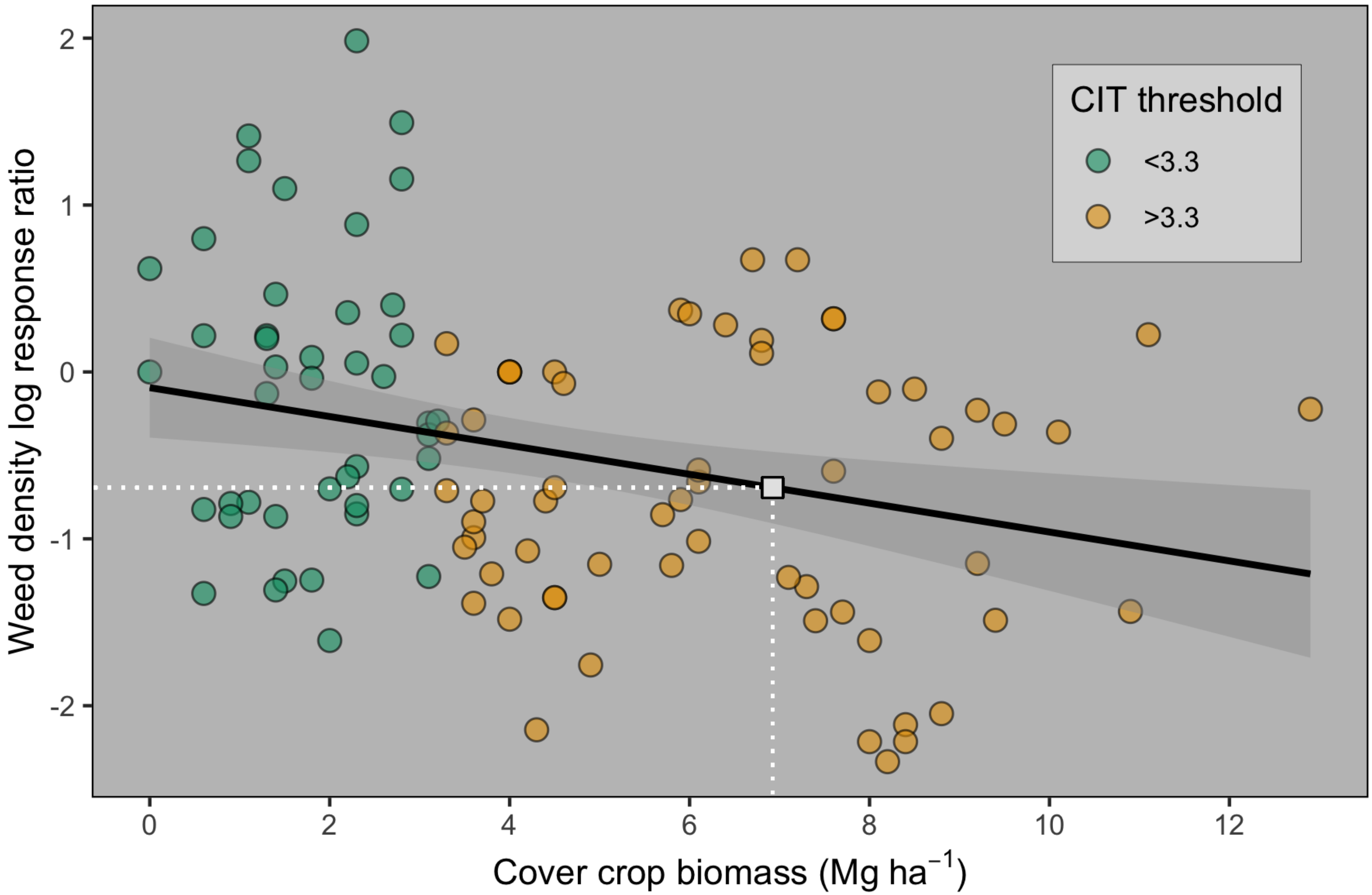
Figure 2.4. LRR_{WDEN} as a function of CC biomass (Mg ha^{-1}). Points are colored based on CIT threshold where green values are those represented in the < 3.3 Mg ha^{-1} terminal node and yellow values are those represented in the > 3.3 Mg ha^{-1} terminal node. The white dotted line represents a 50% reduction in WDEN at an associated CC biomass value of 6.6 Mg ha^{-1}.

Figure 2.5. Crop yield and weed response LRR plotted against each other. The distribution of LRR for crop yield and weeds is presented to the right and above of the graph. Circles and distribution curves correspond to weed biomass (orange) and weed density (blue) values, respectively. Comparisons where CC improved yield and suppressed weed comprised 38% of all points.

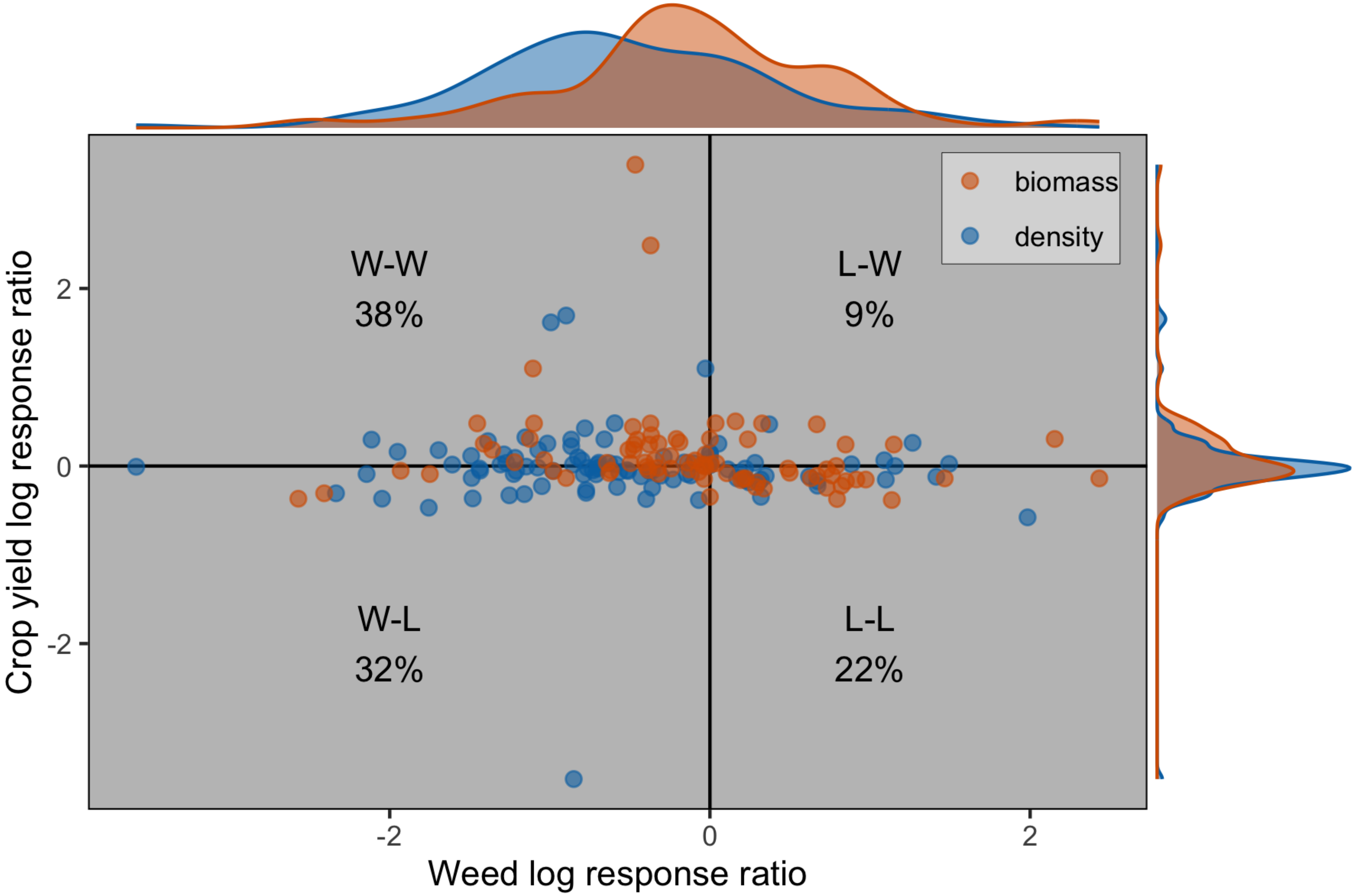

36°N
34°N
32°N
30°N
28°N
26°N
24°N
95°W
90°W
85°W
80°W
75°W
Num. of comparisons
1-5
6-10
12-20
30-43


Weed biomass
Weed density
Crop yield
mean: -21%
n: 142 (14)
mean: -44%
n: 139 (23)
mean: 8%
n: 144 (22)
Kernel density
0.6
0.4
0.2
0.0
2.0
1.5
1.0
0.5
-2
0
2
Natural log of response (CC/no CC)


Node 1
pub_year
N = 139, p = 0
≤ 2002
> 2002
Node 3
cc_bio_Mgha
N = 115, p = 0.046
≤ 3.3
> 3.3
Node 2, N = 24
Node 4, N = 46
Node 5, N = 69
Weed density LRR
2
0
-2
a
b
c



CIT threshold
<3.3
>3.3
Weed density log response ratio
2
1
0
-1
-2
0
2
4
6
8
10
12
Cover crop biomass (Mg ha^{-1})


biomass
density
W-W
38%
L-W
9%
W-L
32%
L-L
22%
Crop yield log response ratio
2
0
-2
-2
0
2
Weed log response ratio

CHAPTER 3

DEMOGRAPHICS OF PALMER AMARANTH IN ANNUAL AND PERENNIAL COVER CROPS[1]

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[1] Weisberger, D., Leon, R., Gruener, C., Levi, M., and N. Gaur and N.T. Basinger. To be submitted to *Weed Science*.

Abstract

Palmer amaranth is the most problematic weed of cotton cropping systems within the Southeast US. Heavy reliance on herbicide-centric weed management has selected for resistant to multiple herbicide modes of action. Effective management of this weed may require the integration of cultural practices that limit germination, establishment, and growth. Cover crops have been promoted as a cultural practice that targets these processes. We conducted a two-year study in Georgia, USA, to measure the effects of two annual cover crops (cereal rye [*Secale cereale* L.] and crimson clover [*Trifolium incarnatum* L.]), a perennial living mulch (Durana® white clover, [*Trifolium repens* L.]), and a bare ground control on Palmer amaranth population dynamics. The study was conducted in the absence of herbicide. Life history traits were integrated into a basic demographic model to evaluate differences in population trajectories. Both cereal rye and living mulch treatments had an order of magnitude greater effect on weed seedling recruitment (seedlings seed^{-1}) than the bare ground control in both years, and the crimson clover in the second year. Low recruitment was correlated with low seasonal light transmission at the soil surface. Low recruitment rates were also correlated with high survival rates. Higher survival rates and reduced adult plant densities resulted in higher biomass (g plant^{-1}) and fecundity (seeds plant^{-1}) values for cereal rye and living mulch treatments in both years. The annual rate of population change (seeds seed^{-1}) was equivalent across all treatments in the first year, but was higher in the living mulch treatment in the second year. Our results highlight the potential of annual cover crops and living mulches in suppress Palmer amaranth seedling recruitment. However, judicious use of herbicide and hand-weeding will continue to play an important role given trade-offs around recruitment, survival, and biomass and fecundity allocation.

Introduction

Over the last 25 years, no weed has had a greater impact on cotton production systems than Palmer amaranth (*Amaranthus palmeri* S. Wats.) (Macrae et al. 2013, Vulchi et al. 2022). Palmer amaranth emerged as the most problematic weed in cotton production systems in the early 2000s shortly after the widespread adoption of glyphosate resistant (herbicide resistant, “HR”) cotton in the Southeast US (Webster et al. 2012). While widespread adoption of HR cotton helped to catalyze increased area under conservation tillage, a sharp reduction in the diversity of herbicide sites of action (SOA) used to manage weeds occurred in tandem (Duke and Powles 2008, Kniss 2018, Vulchi et al. 2022). Because Palmer amaranth seed requires high levels of light for germination and its reproductive and genetic characteristics maintain high levels of diversity, the reduction in both tillage and herbicide SOA diversity helped to create an ideal niche for the selection of resistance to glyphosate, which led to widespread colonization of similar cropping systems in the region (Price et al. 2011, Ward et al. 2013, Roberts and Florentine 2021). Within five years of HR cotton adoption in the Southeast US, cases of glyphosate resistant Palmer amaranth were being reported, and resistance was confirmed in 2006 in the state of Georgia (Culpepper et al. 2006).

As reports of glyphosate resistant Palmer amaranth became more ubiquitous, initial management recommendations to deal with glyphosate resistant Palmer amaranth entailed the use of deep inversion tillage to bury seed, taking advantage of a small seed size and light-dependent germination requirements (Price et al. 2011, Aulakh et al. 2012, 2013). While effective, this ability to “reset” the weed seed bank can only be practiced infrequently, as sequential tillage events may exacerbate Palmer amaranth infestations (Price et al. 2011). Furthermore, tillage adds to production costs and is a major contributor to soil erosion (Price et al. 2011). While the use of diverse herbicide SOAs and newer HR cotton varieties have been promoted since initial cases of glyphosate resistance, Palmer amaranth populations have subsequently been confirmed for eight SOA, many of which are heavily relied upon in cotton production systems (Heap, 2021). Ongoing challenges with herbicide resistance in Palmer amaranth necessitate a transition to weed management systems that rely on varied sources of mortality (Chahal and Aulakh 2016, Korres et al. 2019). To delay resistance and maintain the efficacy of herbicides, reductions in population size coupled with decreased selection pressure imposed on populations must be prioritized (Neve et al. 2011, Menalled et al. 2016). The challenge of doing this, while maintaining the economic and soil-related benefits of conservation tillage systems is considerable given their increased reliance on herbicides in place of tillage (Chauhan et al. 2012, Nichols et al. 2015).

To address this, researchers and farmers throughout the Southeast US have increasingly experimented with cover crops within conservation tillage-cotton production systems to manage Palmer amaranth (Webster et al. 2013, Wiggins et al. 2015b, 2015a, Price et al. 2016, Palhano et al. 2018, Hand et al. 2019). Cover crops are species of annual cereals and forage legumes, which were initially used as a measure to decrease erosion and nutrient leaching (Ruis et al. 2019). Cover crops are established yearly after cash crop harvest in the fall and terminated with herbicide, often in combination with mechanical termination, prior to the subsequent year's cash crop planting. By adding a layer of residue to the soil surface, cover crops have been shown to help suppress weeds primarily by reducing the quantity of light reaching the soil surface, acting as a physical barrier, and altering the soil environment by introducing allelopathic chemicals and by changing temperature and nutrient dynamics (Teasdale, 2018).

Less studied and used are living mulches; annual or perennial plant species that differ from cover crops in that they remain alive synchronously to the cash crop for at least part of the growing season (Paine and Harrison 1993, Hartwig and Ammon 2002, Bhaskar et al. 2021). Herbicide or mechanical termination are used to create strips into which a cash crop is planted while the inter-row area is occupied with living plant species (Hartwig and Ammon 2002, Mohammadi 2012, Westbrook et al. 2022). While many of the same mechanisms that suppress weeds via cover crops apply to living mulches, perennial living mulch species create an even less hospitable environment for annual weed species given the duration of interference that occurs between living mulch and weed (Mohammadi, 2012, Westbrook et al. 2021). While cover crops have been shown to be most effective at suppressing weed germination and seedling emergence, living mulch systems may alter the inter-row resource environment significantly to limit growth, development, and fecundity of weeds as well (Mohammadi, 2012, Teasdale, 2018, Westbrook et al. 2021).

Both cover crops and living mulches offer pathways to maintain or even enhance the benefits of conservation tillage systems. In order to understand the potential benefits and trade-offs between these practices, a cotton cropping system experiment was established in the fall of 2019 using two annual cover crop species (cereal rye [*Secale cereale* L. ‘Wrens Abruzzi’] and crimson clover [*Trifolium incarnatum* L. ‘Dixie’]), a perennial living mulch species (white clover [*Trifolium repens* L. ‘Durana®’]) and a bare ground control under no-till conditions. The study described in this paper, nested within that larger experiment, was developed to quantify differences among treatments with respect to Palmer amaranth population dynamics. As such, this experiment was conducted so that herbicide was used solely to terminate cover crop or living mulch biomass prior to cash crop planting and not at any point as a source of mortality to manage Palmer amaranth. This may be particularly relevant given the almost complete loss of efficacy for certain herbicide SOA in controlling this weed. More so, this allowed us to evaluate the inherent ability of these different cover crop and living mulch species to regulate Palmer amaranth populations at various life history stages. Specifically, we sought to answer the following questions. Are there relative differences in the ability of cover crops or a living mulch species to target vulnerabilities in the life history of Palmer amaranth? How do cover crop and living mulch species differ in their ability to regulate both the abundance (plants m^{-2}), biomass (g $plant^{-1}$) and fecundity (seeds $plant^{-1}$) of this weed at various life history stages? What are the ramifications of changes to abundance and size on reproductive output and demographic processes that may affect subsequent production years?

Materials and methods

Experimental design and site information

The experimental site was established at the J. Phil Campbell Research and Education Center in Watkinsville, GA (33°52′09.5″ N 83°26′59.8″ W) in the fall of 2019. Plots were arranged in a randomized complete block design with 4 replicates. Plots sizes were approximately 11 m x 16.6 m. Treatments in this study included 1. a bare ground control (BG), with no cover crop 2. a leguminous annual cover crop, crimson clover (CC), 3. an annual cereal cover crop, cereal rye (CR), and 4. a leguminous perennial living mulch, white clover, which will be referred to as a “living mulch” herein (LM). Soils at the site were a Cecil sandy loam (fine, kaolinitic, thermic typic Kanhapludults). The site had previously been in no-till production, with the most immediate prior crop being cotton *(Gossypium hirsutum* L.).

Cover crop and fertility management

In 2019, the entire experimental area was chisel plowed and disked on 3 Oct. The area was cultipacked prior to planting on 15 Oct. All treatment species were planted using a 2m 606NT Great Plains no-till drill (1525 E. North Street, Salina, KS 67401), with a row spacing of 19cm at a rate of 22 kg ha^{-1} (CC), 112 kg ha^{-1} (CR), and 22 kg ha^{-1} (LM) on 18 Oct. In the establishment year (2019), the entire area was cultipacked again after planting based on best management practices information from Sanders et al., 2017. In 2020, CC and CR were planted on 24 Nov. in the same manner. Given that LM is a perennial, re-planting was unnecessary. All treatments were managed as no-till after the initial establishment of the experiment. Soil samples were taken on 18 Oct. 2019 to determine initial P, K, and pH levels. On 14 Nov. 2019, fertilizer (450 kg ha^{-1}, 0-15-30) and agriculture lime (1000 kg ha^{-1}) was applied to the entire experimental area to attain P and K levels of 45 and 140 ppm; a pH of 6.2. On 9 and 21 April, 2020 and 2021, CC and CR plots were mechanically terminated with a 2m-wide roller-crimper with a chevron pattern. Roller-crimping was performed when CR was in the early dough growth stage, and CC was in the flowering (full-bloom) growth stage. On 16 Apr. 2020, soils were sampled to determine the need for additional fertilization based on the cotton yield goal of 840 kg ha^{-1}. The entire experimental area was fertilized (400 kg ha^{-1} of 0-0-60) on 6 May. In 2021, soils were sampled, to determine P, K, and pH levels for that season’s cotton production, on 17 May. Based on these results, the entire experimental area was fertilized (560 kg ha^{-1}, 0-20-20) on 6 Jun.

Nitrogen (N) management differed across treatments. All treatments were managed based on the cotton yield goal of 840 kg ha^{-1} with an associated N requirement of 67 kg ha^{1}. In both years, urea-ammonium nitrate (UAN) was applied at the pinhead square stage of cotton development (BBCH 51, Munger et al., 1998). This occurred on 16 and 22 Jul., in 2020 and

2021, respectively. This quantity was provided by adding UAN relative to the N-mineralization (credit) or uptake (debit) of the different cover crop treatments. In both years, BG plots were fertilized with 67 kg ha^{-1} UAN. Fertilization rates for CC and CR treatments were determined by taking 4, 0.25m^{2} quadrat biomass samples, prior to cover crop termination, on 8 Apr. and 20 Apr. in 2020 and 2021, respectively. Sampling followed UGA guidelines for use of the “Cover Crop Nitrogen Availability Calculator”, which approximates N-credits and -debits for different cover crop and tillage systems (Gaskin et al. 2019). In 2020, CC and CR plots received 22 and 67 kg ha^{-1} UAN, respectively. In 2021, CC and CR plots received 0 and 67 kg ha^{-1} UAN, respectively. LM plots received no N fertilizer in either year of the study. Previous work within maize-LM systems in Georgia indicated the potential for cotton crop N-demands to be met solely through mineralization of both above and below ground biomass of the LM through the growing season (Andrews et al. 2018).

Herbicide management

The following section details management of cover crop burndown and ambient weeds. All POST herbicide applications were made to the entirety of the experimental area excluding the area in which demography measurements were taken. Unless otherwise stated, all herbicide applications were either broadcast applied over BG, CC and CR plots or applied in 25 cm bands at a spacing of 90cm for LM plots using a water carrier volume of 187 L ha^{-1}. On 26 Nov. 2019, due to high observed densities of the winter annual weeds, dead nettle (*Lamium purpureum* L.), mouse ear chickweed (*Cerastium vulgatum* L.), and ivy-leaf speedwell (*Veronica hederifolia* L.), 2,4-DB (4-(2,4-dichlorophenoxy)butanoic acid) was broadcast applied over all plots at a rate of 5.97 kg a.i. ha^{-1}. No herbicide was applied in the fall of 2020. On 14 and 22 Apr, 2020 and 2021, after CC and CR cover crops had been roller-crimped, glyphosate (N-

(phosphonomethyl)glycine) was applied at a rate of 3.12 kg a.i. ha^{-1}. On 13 and 25 May, 2020 and 2021, one day prior to planting, paraquat (1,1′-dimethyl-4,4′-bipyridinium) was applied at a rate of 723 g a.i. ha^{-1}. On 8 and 18 Jun., 2020 and 2021, a POST 1 herbicide application of glyphosate was applied at a rate of 1.56 kg a.i. ha^{-1}. This was followed on 20 and 29 Jul., 2020 and 2021, with a layby (POST direct) application of glyphosate plus carfentrazone (N-(phosphonomethyl)glycine) + carfentrazone-ethyl) applied at a rate of 1.56 kg a.i. ha^{-1} + 7 g a.i. ha^{-1}.

Cotton management

On 14 May, 2020 and 26 May, 2021, the cotton cultivar DG 3615 B3XF was planted at a population of 87,500 plants ha^{-1} with a row spacing of 90cm. All treatments were planted with a John Deere 7300 MaxEmerge2 (Deere & Company, One John Deere Place, Moline, IL 61265) with row cleaners. Plot size allowed for 12 rows of cotton within each treatment plot. All plots were provided with supplemental irrigation, when necessary, to meet weekly irrigation totals recommended by UGA extension guidelines (Whitaker et al., 2018). Mepiquat chloride (N,N-dimethylpiperidinium), a commonly-used growth regulator, was applied in-season based on UGA Extension guidelines (Whitaker et al. 2018). In 2020, BG, CC and CR plots received 37, 25 and 50 g a.i. ha^{-1} mepiquat chloride on 27 Jul., 12 and 27 Aug, respectively. In 2020, LM plots received no growth regulator. In 2021, BG, CC an CR plots received 37 g a.i. ha^{-1} mepiquat chloride on 28 Jul. No growth regulator was applied to the LM plots on this date. On 23 Aug., all treatment plots received 50 g a.i. ha^{-1} mepiquat chloride. On 26 and 22 Oct. of 2020 and 2021, a harvest aid was applied to all plots based on UGA Extension guidelines (0.84, 2.1, 26 + 13 g a.i. ha^{-1} of Tribuphos [S,S,S-Tributyl phosphorotrithioate], Ethephon [(2-chloroethyl)-phosphonic acid] and Thidiazuron [N-phenyl-N'-1 ,2,3-thiadiazol-5-ylurea] + Diuron [3-(3,4-dichlorophenyl)-1, 1-dimethylurea]) (Whitaker et al. 2018).

Weed demography measurements and modelling

After cover crops were planted in the fall of 2019, Palmer amaranth was seeded in 3 x 3m subplots, within each plot, at a density of approximately 25,000 seeds m^{-2} based on a 1000 seed weight of 0.34 g. Our experimental site (J. Phil Campbell Research and Education Center, Watkinsville, GA) was selected due to a complete lack of background population of the weed of interest. This allowed us to introduce and accurately assess the population dynamics of an artificially generated population of Palmer amaranth. To generate an initial population, Palmer amaranth seed was harvested from a local population of mature plants at the Iron Horse Research Farm in Watkinsville, GA (33°72′37.7″ N 83°30′35.1″ W) in early Oct 2019. Following a procedure adapted from Bertucci et al., (2020), mature female plants were stripped of terminal and axillary flowers. This material was air dried at an ambient temperature of approximately 21 C for approximately 2 weeks. The seeds and chaff were hand- and machine-threshed, using a combination of repurposed textured rubber mats and a Humboldt soil grinder (Humboldt Manufacturing Company, 875 Tollgate Road, Elgin, IL 60123). Material was sieved between hand and machine-threshing to remove large pieces of chaff. After threshing, the remaining material was cleaned using a compact Oregon seed blower (Hoffman Manufacturing, 2397 NW Kings Boulevard, Corvallis, OR 97330). An initial germination assay was performed on the harvested seed by taking 10, 1000-seed lots from the cleaned seed and placing those within petri dishes between moist filter paper at ambient room temperature (25 C). Germination was monitored approximately every 3 days and the filter paper was rewetted until a week passed without germination. Based on this, germinability was determined to be approximately 95%.

In the first year of the study, subplots were established with 0.6 m wide drop seeder on 23 Oct. 2019 using a mixture of sand and weed seed to ensure uniform distribution of the weed seed within the established subplot. The germinable seed bank, the fraction of surviving non-dormant seeds from which seedlings may emerge over the course of the season, was determined by taking 20, 2.5cm-diameter soil cores to a depth of 5cm in each subplot of the experiment on 25 and 27 May, 2020 and 2021. Soil cores were manually broken apart and spread over 5cm of a sterile media within a 25 x 50cm plastic tray one day after collection. Flats were kept in a greenhouse and watered daily. Palmer amaranth seedlings were counted on a weekly basis over a 12-week period. The sum of all seedling counts was used to determine the size of the germinable seed bank (seeds m^{-2}) for each distinct treatment x replicate experimental unit.

In-field seedling recruitment was monitored within a 2 x 2m area within each subplot across all 16 plots. Seedling counts were initiated approximately 1 week after planting (WAP) and were conducted approximately every 2 weeks until 9 WAP for a total of 5 measurement time points. This was initiated on 21 May and 3 Jun, 2020 and 2021. Work has shown that upwards of 85% of Palmer amaranth seedlings emerge from mid-May through early August, suggesting that monitoring seedling emergence over this extended period should provide a reliable estimate of a total seedling population (Jha, 2010). Seedling counts were made using colored toothpicks to quantify emerged seedlings. A $1m^2$ gridded quadrat, divided into 100, 10 x 10cm cells using colored cable was used to help guide seedling counts for measurements at 1, 3, and 5 WAP for all treatment. At 7 and 9 WAP seedling measurements, where larger, earlier-emerged seedlings had grown large enough to prevent the use of the gridded quadrat, any emerged seedlings not already marked by toothpicks were counted.

Adult plants were harvested over a week-long period, on a per-rep basis, beginning on 5 and 12 October, 2020 and 2021. Adult plants were carefully removed from each subplot using hand-held serrated sickles, and counted. Adult plants were placed into 3.78 L yard waste bags and air dried for approximately 2 weeks at ambient temperatures (25 C). Plants were removed from the bags and female plants were then threshed using the same process as that described above, with the exception being that plants were processed by rep and treatment (n = 16). Distinct seed lots were established in this way. A small subsample (1g) was removed from each seed lot and counted to determine 1000 seed mass. This was used to determine fecundity values for each experimental unit. Palmer amaranth seed from each experimental unit was hand-broadcast into the associated subplot area on 9 December 2020 for 2021 measurements.

The data described above were used to quantify Palmer amaranth at various life history stages, and calculate the effect of our experimental treatments on life history transitions from the seedbank to seedling (recruitment, *r)*, seedling to adult plant (survival, *s)*, as well as the reproductive capacity of adult female plants, (fecundity, *f*). These demographic parameters can be plainly described as the quantity of seedlings seed^{-1}, plants seedling^{-1}, and seeds plant^{-1}, respectively. Following the approach taken in Heggenstaller and Liebman (2005), who adapt a single-cohort model from Cousens and Mortimer (1995), our goal was to quantify differences in weed population dynamics under different cover crop treatments by using a simple model that, "relates weed population density at the end of the growing season to weed population density at the beginning of the season as a function of rates of cumulative seedling recruitment (r), seedling survival (s), plant fecundity (f)". This is expressed as:

$$N_{EOS} = N_{BOS} - N_{BOS}(r) + N_{BOS}(r \times s \times f) \quad [1]$$

Dividing this entire equation by the number of individuals at the beginning of the season (N_{BOS}) provides an estimate of the annual change in population size from the beginning to the end of the season. The resulting quotient can be understood as the quantity of new seeds added to the population at the end of the season relative to each seed added to the population at the beginning of the season (N_{EOS}/ N_{BOS}). This annual rate of population change (Δ) is expressed as:

$$\Delta = 1 - r + (r \times s \times f) \quad [2]$$

This simple model has its limitations. As mentioned in Heggenstaller and Liebman (2005), Δ does not account for seed losses due to microbial decay, reduced germinability due to aging, and granivory from both vertebrate and invertebrate sources, all of which can contribute seed losses (Liebman et al., 2004). Additionally, Palmer amaranth is a dioecious species producing separate male and female plants (Ward et al. 2013). Fecundity rates in this study were calculated from seed produced on adult female plants. While sex ratios (female: male) and synchrony around anthesis can certainly impact fecundity and therefore demographic trajectories, recent work suggests that under non-water limiting conditions, such as those in which this study was conducted, sex ratios in populations of Palmer amaranth do not significantly differ from 1:1 (Mesgaran et al., 2021). More so even, quantifying this response was not one of the goals of this work, and has no bearing on the calculations of the annual rate of weed population change used in this study.

Measurement of explanatory variables (cover crop biomass, light transmission, and soil moisture)

As mentioned, previous work suggests that cover crops may suppress weeds by creating a physical barrier (impeding emergence), altering the quantity of light reaching the soil surface (reducing requirements for germination), and changing soil temperatures (lowering soil temperature below that required for germination) (Teasdale, 2018). To account for the effect of these variables, we measured above ground biomass of each treatment at planting (Table 3.1), as well as light transmission and soil temperature over the course of the growing season. Above ground treatment biomass for all treatments was assessed on 15 and 26 May, in 2020 and 2021 by removing 4, 0.25m^2 quadrat samples along a transect within each plot. These were dried at 85C for 3d and weighed. To estimate light transmission to the soil surface for each treatment seasonally, a ceptometer (ACCUPAR LP-80, Meter group, 2365 NE Hopkins Court, Pullman, WA, 99163) was used every 2 weeks starting with 1 week after planting (WAP) and ending at 9 WAP. These began on 21 May and 3 Jun, 2020 and 2021. Measurements were made between 10am and 2pm by taking an ambient reading and then by either placing the ceptometer at soil level or sliding it under cover crop or living mulch residue. Soil temperature measurements were initiated at the same time and followed the same temporal pattern. A soil-moisture meter (TDR FieldScout 350, Spectrum Technologies, 3600 Thayer Court, Aurora, IL 60504) was fitted with 5cm probes and used to record soil temperature at that depth. For both light transmission and soil temperature measurements, 4 measurements (2 intra-row and 2 inter-row) were made in an area directly adjacent to our weedy subplot area over 5 time points within each season. Sampling occurred adjacent to weedy subplots to avoid the confounding effect of the weed canopy over the course of the season. Ambient temperature data were extracted as growing degree days (GDDs) via the UGA weather network (www.georgiaweather.net) from the nearest weather station (approximately 100m distance from study). GDDs were calculated using a base temperature of 10 C, which has been established as the lower threshold for growth for Palmer amaranth (Jha et al., 2010) (Table 3.2).

Statistical analyses

All analyses were conducted using JMP 16 Pro (JMP, Version 16. SAS Institute Inc., Cary, NC). Above ground treatment (cover crops and bare ground) biomass data were expressed on a kg ha^{-1} basis (Table 3.1). All demographic parameters (recruitment, survival, and fecundity) were expressed as rates calculated from measurements of seedbank, seedling, and adult plant densities, as well as seed production per adult female plant. Adult plant density and weed biomass data were analyzed on m^{-2} and plant^{-1} bases. Data relative to the variables mentioned above were either log$_e$ or square-root transformed to meet the assumptions of normality. Analysis of variance (ANOVA) was performed, considering year and treatment as fixed factors and replicate as a random factor using the Standard Least Squares procedure. Preliminary analyses indicated significant year x treatment interactions for most variables. Consequently, all analyses were conducted separately for each year. Treatment means are reported as least square means, and were separated using Tukey's HSD ($\alpha = 0.05$).

Light transmission data were analyzed as the percentage of light reaching the soil surface by using the following equation:

$$\text{Light transmission to soil surface} = [1 - (\text{light at soil surface}/\text{ambient light})] \times 100 \quad [3]$$

Light transmission and soil temperature data were both subject to repeated measures analysis in each year using a Mixed Model and a toeplitz covariance structure (Littell et al., 2006). The model included fixed terms for treatment, sampling location (inter-row or intra-row), WAP, and interactions therein, and a random term for replicate. *A priori* determined comparisons of treatment variables at each measurement timing (WAP) within each year were analyzed by-sampling location.

Lastly, due to considerable variance, seasonal (as opposed to cumulative) seedling recruitment data were transformed by dividing the quantity of emerged seedlings at a given time point over the sum of emerged seedlings over the entire season (percent seasonal seedling recruitment). Within each year, the relationship between the percent seasonal recruitment and WAP for each treatment was fit to a 2-parameter logistic model,

$$y = \frac{1}{1+\exp(-a(x-b))} \quad [4]$$

where *y* is percent in-season seedling recruitment, *a* is growth rate, *b* is the inflection point (representing 50% of cumulative recruitment), and *x* is WAP (Ritz et al., 2015). A $R^2_{\text{nonlinear}}$ value was estimated for each curve based on the following calculation (Ritz et al., 2015):

$$R^2_{\text{nonlinear}} = 1 - (\text{Residual sum of squares/Corrected total sum of squares}) \quad [5]$$

Results and discussion

Above ground biomass, light transmission, and soil temperature

In 2020, above-ground biomass for all cover crop treatments was greater than the BG treatment (Table 3.1). The mean value for above ground biomass across all three cover crop treatments was 6032 kg ha^{-1} while that of BG, which comprised the winter annual weeds mentioned above, was 560 kg ha^{-1}. In 2021, above ground biomass was least in the BG treatment, followed by CC, LM and CR. Associated mean values were 228, 1765, 2744, and 4875 kg ha$^{-1,}$ respectively. Higher biomass values for all treatments in our first year were the result of an earlier planting date in the fall of 2019 relative to that of 2020 (15 Oct. vs. 24 Nov.). This earlier planting was informed by best management practices in Sanders et al., 2017, whose work on LM system optimization using corn (*Zea mays* L.) as a cash crop highlighted the importance of an early planting to ensure proper stand establishment of the white clover cultivar (Durana®) being used. Given this, in 2020 above ground biomass values for our annual cover crop species (CC and CR) were closer to those presented in Webster et al., 2013, who measured multiple annual cover crop species at a lower latitude than our site where milder winter temperatures and a faster accumulation of GDDs in the early spring allow for the production of considerable biomass (Webster et al., 2013). 2021 values for CC and CR were similar to those reported in studies conducted within a lower latitude range (Price et al. 2016; Palhano et al., 2018). LM biomass values were greater than those reported in studies conducted at the same site in previous years. This was true for the establishment-year and first-full year of growth, and may be as a result of higher initial seeding rates used in our study (Andrews et al. 2018, Sanders et al. 2017).

In both years of the study, our analyses indicated significant treatment by WAP interactions for inter-row measurements of light transmission to the soil surface. In both years, the quantity of light reaching the soil surface was greatest for the BG treatment, followed by CC, and then CR and LM, which were almost identical to each other, over nine weeks of measurements (Fig. 3.1). In 2020, this trend remained constant until 9 WAP, when light transmission values were the same across all treatments, coinciding with canopy closure of the cotton crop (Fig. 3.1). In 2021, light transmission values for BG and CC treatments were equivalent by 7 WAP, but greater than CR and LM. In 2021, by 9 WAP light transmission values were the same across all treatments because of canopy closure of the cotton crop (Fig. 3.1). These results are a direct reflection of the quantity and quality of above ground biomass for each treatment. Analysis of intra-row data for 2020 indicated a significant treatment x WAP interaction; however, means separations revealed differences in light transmission values only at a singular timepoint (7 WAP), where BG and LM values were significantly greater (data not presented). At all other time points, light transmission values were the same across treatments, and gradually decreased over the course of the 9 weeks. 2021 data analysis similarly indicated that light transmission decreased over the season (effect of time, WAP), but did not differ as a result of treatment.

Above ground biomass in the BG treatment consisted of several winter annual weed species, which produced limited biomass and degraded rapidly due to a combination of senescence and the effects of our burndown herbicide application. This had a limited to zero effect on reducing light transmission at the soil surface. Differences in light transmission values among CC, CR and LM may be explained by factors such as above ground biomass, residue quality and plant life cycle for these different species. Given that the underlying pedology, meteorological conditions and management (e.g. irrigation) were relatively uniform across all treatments in our study, the persistence of above ground biomass for annual cover crops in our study was strongly correlated with the quantity of biomass at termination and its C:N ratio (Thapa et al. 2022). This is evidenced by the higher degree of light transmission in CC relative to CR treatments. While above ground biomass for these two species was equivalent in 2020, light transmission was greater in CC treatments. We posit that this is a result of having a higher relative C:N ratio and hence a faster rate of decomposition. Conversely, low levels of light transmission in the CR treatment were associated with higher mean biomass values, a residue having lower relative C:N ratio, and slower decomposition over the course of the growing season (Thapa et al. 2022). According to Andrews et al., 2018, plant available nitrogen values for CC and LM treatments were similar in the first 90 days after planting. This suggests that decomposition rates for these two species may be similar and that low transmission values in the inter-row of the LM treatment arose due to its perenniality rather than residue quality.

Intra-row light transmission values were almost identical across treatments in both years, suggesting that the effects of management generated similar light environments within this area over all treatments. As mentioned, the planter we used (John Deere 7300 MaxEmerge2, Deere & Company, One John Deere Place, Moline, IL 61265) had row cleaning units, a feature that moves residues away from the crop row to facilitate earlier crop emergence. Functionally, this may have duplicated the lack of residue in the BG treatment, and the reduced quantity of residue present in the intra-row of LM (due to banded herbicide application), across all treatments.

Lastly, cumulative GDD_{10} values from May through October are presented in Table 3.2. These data were relatively uniform, by month, across both years of the study, peaking in July and August, and decreasing after that time period until October. We did not find significant treatment by WAP interactions in either year of the study for soil temperature (data not presented). Soil temperatures increased over the 9 weeks of measurements, in all treatments, at the depth in which the probe measured (5 cm) following the trend described above. This was true under both inter- and intra-row areas. While optimal measurement of this parameter would have entailed the use of an *in situ* sensor, our measurement methodology and findings are similar to a cotton-cover crop study conducted in North Carolina, where the presence of a CR/CC mixture did not alter soil temperature relative to a BG treatment (Vann et al. 2018).

Seedling recruitment

In 2020, cumulative seedling recruitment rates differed between BG and all cover crop treatments (Table 3.3). The untransformed recruitment rate for the BG treatment was approximately one order of magnitude greater than the rate averaged over the three cover crop treatments (0.192 vs. 0.022 seedlings seed^{-1}). This amounts to a difference of 568 vs. 66

seedlings m^{-2} for BG vs. the mean of all other treatments (data not shown). Patterns of seasonal recruitment also differed across treatments. Parameter estimates from the logistic model show that the growth rate for BG was almost twice that of the cover crop treatments, and that 50 percent of total recruitment was reached in just under 3 WAP (Fig. 3.2 and Table 3.4). In contrast, the growth rates were reduced under CC, CR and LM treatments. However, the CC treatment fared less favorably relative to CR and LM treatments with respect to the time point at which 50 percent recruitment occurred (Fig. 3.2 and Table 3.4). The CC treatment reached this at approximately 3.5 WAP, while CR and LM treatments were closer to 4.5 WAP. In 2021, cumulative seedling recruitment rates were different between BG and CC treatments, and CR and LM treatments (Table 3.3). Untransformed differences, averaged over each means separation grouping (BG/CC vs. CR/LM), were 0.248 and 0.016 respectively, representing an even greater magnitude of difference between recruitment rates as a function of treatment. This translates to a difference in cumulative emerged seedlings of 920 vs. 26 seedlings m^{-2} between treatment groupings (data not shown). This was also reflected in parameter differences in the logistic models (Fig. 3.2 and Table 3.4). Recruitment growth rates were two and a half to almost four times greater when comparing BG and CC treatments with CR and LM treatments (Fig. 3.2 and Table 3.4). Likewise, BG and CC treatments reached 50% seedling recruitment by just over 1.5 WAP, while this was delayed by 1-1.5 weeks for CR and LM treatments respectively (Fig. 3.2 and Table 3.4).

As mentioned, light and temperature are important requisites for the germination and emergence of Palmer amaranth (Reinhardt Piskackova et al. 2021, Ward et al. 2013). Differences in both cumulative and seasonal seedling recruitment rates among treatments and between years were strongly related to these factors, and to the degree that these were attenuated by both the quantity and persistence of our cover crop treatments. In 2020, cumulative recruitment rates were lower in all cover crop treatments as a function of the quantity of biomass produced relative to the BG treatment, and the lower relative light transmission values; variables that are inherently coupled (Tables 3.1 and 3.3). Seasonal recruitment rates differed across cover crop treatments, with a greater proportion and early recruitment occurring in the CC treatment relative to CR and LM treatments (Fig. 3.2, Table 3.4). This suggests that while residue quality and decomposition rates differed across cover crop treatments, all treatments met a minimum biomass threshold to maintain sufficiently low light levels, and subsequently cumulative recruitment rates, at an equivalent level across those species. With respect to annual cover crops, biomass quantity, regardless of species, has been shown to be a key factor in weed suppression, which supports the findings from our first year (Aulakh et al. 2012, MacLaren et al. 2019, Nichols et al. 2020, Osipitan 2018, Osipitan et al. 2019).

In 2020, Higher relative above ground biomass values for CC may have masked residue quality and persistence differences, but this was not the case in 2021. The later cover crop planting date (Nov. 24 vs. Oct. 15) resulted in less CC growth relative to CR and LM. Lower above ground biomass coupled with a residue prone to faster decomposition translated into higher mean values of inter-row light transmission in 2021 (Fig. 3.1, Table 3.1). Mean above ground biomass for CC in 2021 (1765 kg ha^{-1}) was below a threshold to have any suppressive effect on cumulative seedling recruitment, and did not differ from the BG treatment for this variable (Table 3). This was mirrored in the model of seasonal seedling recruitment over the measurement period, where BG and CC lines and parameters were identical (Fig. 3.2, Table 3.4). Both CR and an established stand of LM are more productive per unit time, due to faster growth rates under lower temperatures and a longer period of resource capture and growth, respectively

(Ruis et al. 2019, Bhaskar et al. 2021). Additionally, CR residue is slower to decompose, while LM maintains high surface area coverage with living plant biomass through the growing season, factors that help to explain the low light and recruitment rates under these treatments (Ruis et al. 2019, Bhaskar et al., 2021).

Differences in both cumulative and seasonal recruitment rates were also strongly moderated by cotton planting dates and thus measurement timing. While accumulated GDDs did not vary much between years and by month (Table 3.2), our measurements of emerged seedlings in 2020 began on May 21, while in 2021 they began on June 2. This difference amounts to an additional 50 GDDs that weed seedlings and seeds had experienced at the time of our 1 WAP measurement in 2021.

Seedling survival

In 2020, square root transformed seedling survival rates were lowest for BG (0.118), followed by CR (0.475), and then CC/LM (0.649) (Table 3.3). In 2021, these rates were lowest for BG/CC (0.190) and highest for CR/LM (0.728) (Table 3.3). Overall, these data portray an inverse relationship between survival and recruitment (Table 3.3). Seedling survival is influenced by resource availability, which is altered via intraspecific competition, and other mortality factors such as herbivory, disease, and abiotic variables (Mohler, 2004). This is particularly true in our study given the absence of direct control measures (i.e., herbicide), which would otherwise serve as the primary source of seedling mortality. Generally speaking, when resource availability is relatively fixed (e.g. sunlight, fertility and moisture), treatments that select for high seedling density (e.g. BG in both years, and CC in 2021) will exhibit greater seedling mortality and lower rates of survival as a function of increased competition between individuals; this is known as density-dependent mortality and appears to be the major driver affecting seedling survival in our study (Harper, 1967, White and Harper, 1970).

While we did not measure the impact of other mortality factors on seedling survival, we did observe the presence of the specialist herbivore *Disonycha glabrata*, a native flea beetle, on Palmer amaranth seedlings and in areas, significant herbivory. *Amaranthus* species, including Palmer amaranth, are hosts to this insect and can incur substantial damage to leaf surface area, particularly during juvenile life history stages (Hemenway 1968, Vorsah et al. 2020). While we did not quantify the abundance of individuals within each treatment area, higher densities of *Disonycha glabrata* were associated with larger patch sizes of Palmer amaranth. Based on Vorsah et al., 2020, the absence of ground cover (i.e., cover crop residue or living biomass) may reduce damage to host plants by altering the life cycle of *Disonycha glabrata* suggesting that cover crops and their indirect effects on Palmer amaranth abundance may discourage populations of this insect. While, to our knowledge, *Disonycha glabrata* has not been explored as a potential biocontrol agent for Palmer amaranth, observations from our study suggest that it warrants further investigation, with consideration of trade-offs around its efficacy relative to cover crops.

Adult plant density, biomass, and fecundity

While the role of density dependent mortality is evidenced by the inverse relationship between recruitment and survival rates (Table 3.3), surviving adult plant densities were proportional to cumulative seedling densities. For example, adult plant density was greatest for the BG treatment (67 and 27 plants m^{-2}) and least for the LM treatment (9 and 10 plants m^{-2}) in both years of the study, corresponding to the highest and lowest cumulative seedling densities in both years (data not shown), and associated cumulative recruitment rates (Fig. 3.3, Table 3.3).

While some nuance around adult plant density occurred with respect to CC and CR treatments between years, the relationship between cumulative seedlings and surviving adult plants is supported by strong correlations between these two parameters in both years of the study ($R^2 = 0.88$, $p < 0.001$ in 2020 and $R^2 = 0.64$, $p < 0.001$) and is an established feature of population biology of annual plants, and particularly annual weeds (White and Harper, 1970, Cousens and Mortimer, 1995).

Adult plant biomass m^{-2} did not differ across treatments (data not shown). Mean values of biomass per m^{-2} across all treatments were 690 g and 348 g in 2020 and 2021, respectively. Given management (i.e. resource) similarity across treatments, the lack of difference among treatments reflects the degree to which both density dependence and carrying capacity regulate total aboveground biomass production per unit area (Weiner et al. 2001, Chu et al. 2008). However, the allocation of aboveground biomass plant^{-1} did differ substantially (Fig. 3.4). In both years, mean aboveground biomass plant^{-1} was greatest in the LM treatment (120 and 73 g) and smallest in the BG treatment (14 and 8 g), with CC and CR treatments having intermediate levels of aboveground biomass plant^{-1} in 2020 and 2021, respectively (Fig. 3.4). Our results demonstrate that aboveground biomass allocation functions inversely to adult plant density, a feature of plants exhibiting a high degree of plasticity, of which Palmer amaranth is a salient example (Ward et al. 2013, Bravo et al. 2017, 2018, Roberts and Florentine 2021).

Fecundity rates (seeds plant^{-1}) followed the same pattern across treatments in both years of the study, where BG, CC treatments had the lowest fecundity rates, followed by CR, and then LM, which had the highest fecundity rates (Table 3.3). Fecundity rates can be tied directly to biomass plant^{-1}. Individual plants, particularly annuals in disturbed environments, with greater biomass tend to have greater fitness and therefore produce greater quantities of seeds (Weiner, 2004). In both 2020 and 2021, the correlation coefficients between $\log_e$ transformed fecundity and biomass plant^{-1} values were 0.79 and 0.84 ($p < 0.0001$), respectively, supporting this phenomenon. Upstream effects of our cover crop treatments on initial seedling population size altered patterns of allocation and fecundity rates. However, fecundity values were different between CR and LM treatments despite having the same quantity of surviving adult plants in both years (Fig 3.3, Table 3.3). This highlights the idea that below ground processes may alter demographic processes, particularly as they relate to fecundity rates. A similar study of cover crop and LM systems in corn production documented sizable relative improvements, under the same LM species, for a suite of soil parameters. These included rates of infiltration, N mineralization and labile carbon accumulation in relation to BG, CC and CR treatments (Hill et al. 2021). Improvements to these soil parameters can have meaningful effects on crop productivity and overall cropping system sustainability, but these benefits appear to accrue to weeds in these systems as well. The two-fold increase in fecundity rate in LM treatment plants in the second year of our study, and stable or decreased fecundity rates in all other treatments over both years (Table 3.3), suggests a soil-mediated change in plant nutrient status over the course of the season and an associated increased in fecundity. Cropping systems using LM could create soil-based legacy effects that may alter weed growth and reproductive output differentially going forward, but further work is necessary to clearly explain the mechanisms by which this appears to occur.

Annual rate of weed population change (Δ)

In 2020, the annual rate of population change was greatest for BG, followed by CC/LM, and least for CR (Table 3.3). 2021 values were the same across BG, CC, and CR, but higher in LM (Table 3.3). In both years, annual rates of population change for all treatments, regardless of intra-annual differences, were positive. In the absence of additional management tactics, we can expect continual additions of weed seed to the seed bank. The annual rate of weed population change is a multiplicative function involving recruitment, survival, and fecundity (Eq. 1 and 2). In our study, low rates of recruitment were associated with high rates of survival and fecundity, with the inverse also being true. As mentioned in the sections above, Palmer amaranth is remarkably plastic and individual plants not controlled by herbicide or mechanical interventions are extremely efficient at producing large quantities of seed in the absence of intra-specific competition. When dealing with a weed species such as Palmer amaranth, where fecundity rates are potentially very high, population growth is unavoidable unless recruitment and survival rates are essentially driven to zero. This phenomenon has been demonstrated in a modelling study involving another species in the genus with similar characteristics, *Amaranthus tuberculatus* (Moq.) J.D. Sauer (waterhemp) (Liebman et al. 2021). In that work, requisite herbicide efficacy levels to reduce population growth even under a CR scenario were only marginally different from the BG scenario indicating that despite the presence of a cover crop, the demographic trajectory of that weed species would increase if even a single female plant remained (Liebman et al. 2021). This management reality of highly fecund weed species has been demonstrated clearly in Arkansas where certain counties have implemented zero-threshold strategies (eliminating all seed producing plants from a field) in order to reduce populations of herbicide resistant Palmer amaranth (Norsworthy et al. 2014).

Conclusion

The results of the current study highlight the impact that certain cover crop and living mulch species can have in regulating the quantity of weed seedlings recruited from the seed bank. However, the continued need for judicious herbicide use to further reduce recruitment and particularly survival rates cannot be overstated. Our findings suggest potential synergies between cover crop use and herbicides, reflecting the need for a diverse set of approaches, particularly when managing highly fecund weed species such as Palmer amaranth. Despite large weed seed additions in both years of the study and associated seed banks, recruitment rates in CR and LM treatments remained very small. This suggests a greater “suppressive resilience” of these species with respect to weed infestations. Even under heavy infestation levels, these species maintained very low levels of seedling recruitment. Limiting cumulative seedling recruitment and “slowing” seasonal recruitment patterns is essential to reduce the selection pressure of herbicide on weeds to maintaining their efficacy and utility. This is essential in cropping systems dealing with the presence of multiple herbicide resistant Palmer amaranth**.** The suppressive resilience of these species is tied directly to the quantity of light that reaches the soil surface over the course of the growing season, which is modulated by the quantity and persistence of above ground biomass. Biomass production is a function of accumulated heat units between cover crop planting and termination. Current agronomic production systems, cotton included, often use longer season crop varieties to optimize their productive and therefore economic potential, which may limit the potential of annual cover crops and compromise the ability to optimally establish a living mulch. Successful yearly or initial establishment of cover crops and living mulches must consider how and when planting can occur in relation to crop rotation and cultivar choice to maximize their contribution to weed management.

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Table 3.1. Biomass (kg ha^{-1}) values for bare ground (BG), crimson clover (CC), cereal rye, and living mulch (LM) treatments in 2020 and 2021. Mean values within a column followed by the same letter are not significantly; Tukey's HSD ($\alpha = 0.05$).

	2020	2021
BG	560 a	228 a
CC	4955 b	1765 ab
CR	7118 b	4875 c
LM	6023 b	2744 bc

Table 3.2. Accumulated monthly growing degree days (base 10 C) from May to October in Watkinsville, GA, USA for 2020 and 2021 growing seasons.

	May	June	July	August	September	October
2020	284	400	509	467	348	250
2021	302	421	472	475	348	239

Table 3.3. Rates of seedling recruitment (seedlings seed^{-1}), survival (plants seedling^{-1}), fecundity (seeds plant^{-1}) and Δ (seeds seed) for bare ground (BG), crimson clover (CC), cereal rye, and living mulch (LM) treatments in 2020 and 2021. Values are presented as raw and transformed data from left to right. Mean values within a column followed by the same letter are not significantly; Tukey's HSD ($\alpha = 0.05$).

	Seedlings seed^{-1}	√Seedlings seed^{-1}	Plants seedling^{-1}	√ Plants seedling^{-1}	Seeds plant^{-1}	Log$_e$ seeds plant^{-1}	Seeds seed^{-1}	Log$_e$ seeds seed^{-1}
2020								
BG	0.192	0.430 a	0.118	0.342 b	2191	7.623 b	45.5	3.77 a
CC	0.040	0.186 b	0.392	0.615 a	2422	7.756 b	27.6	3.26 ab
CR	0.016	0.126 b	0.227	0.475 ab	3863	8.150 ab	14.7	2.57 b
LM	0.010	0.094 b	0.475	0.684 a	12396	9.2581 a	40.5	3.54 ab
2021								
BG	0.282	0.528 a	0.026	0.161 b	1050	6.935 b	8.44	2.08 b
CC	0.214	0.442 a	0.054	0.219 b	2489	6.972 b	10.5	2.14 b
CR	0.011	0.133 b	0.734	0.842 a	3221	7.940 ab	12.9	2.51 b
LM	0.021	0.091 b	0.388	0.614 a	22058	9.275 a	99.5	4.07 a

Table 3.4. From left to right, by-year, mean values and 95% confidence intervals (in parentheses) for model parameters (growth rate [*a*] and inflection point [*b*]), and $R^2_{\text{nonlinear}}$ values for bare ground (BG), crimson clover (CC), cereal rye (CR) and living mulch (LM) treatments in 2020 and 2021.

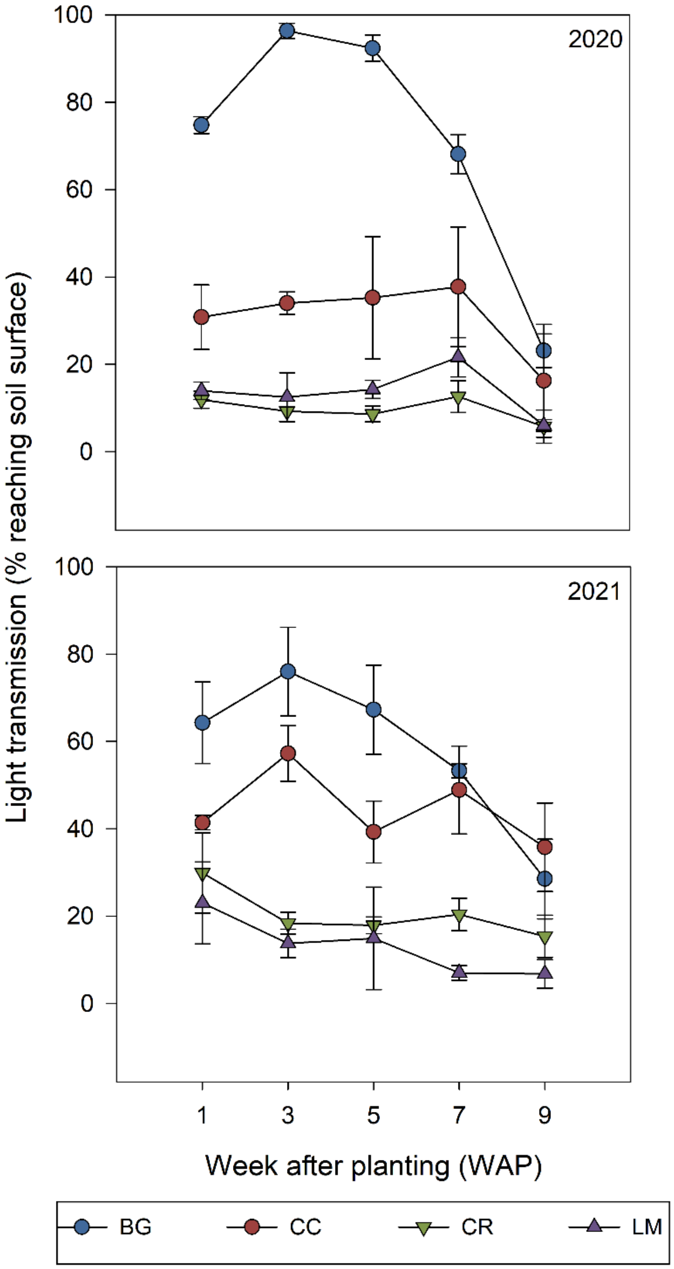
	2020			2021		
	Growth rate (*a*)	Inflection point (*b*)	$R^2_{\text{nonlinear}}$	Growth rate (*a*)	Inflection point (*b*)	$R^2_{\text{nonlinear}}$
BG	1.64 (0.23, 3.05)	2.86 (2.50, 3.23)	0.96	3.47 (-1.78, 8.73)	1.59 (0.68, 2.51)	0.96
CC	0.87 (0.49, 1.25)	3.38 (2.84, 3.92)	0.79	3.19 (-0.76, 7.14)	1.56 (0.85, 2.27)	0.96
CR	0.85 (0.50, 1.21)	4.48 (3.93, 5.02)	0.94	0.91 (0.68, 1.13)	2.62 (2.34, 2.91)	0.92
LM	0.71 (0.44, 0.99)	4.47 (3.88, 5.07)	0.94	1.23 (0.86, 1.61)	3.07 (2.84, 3.31)	0.90

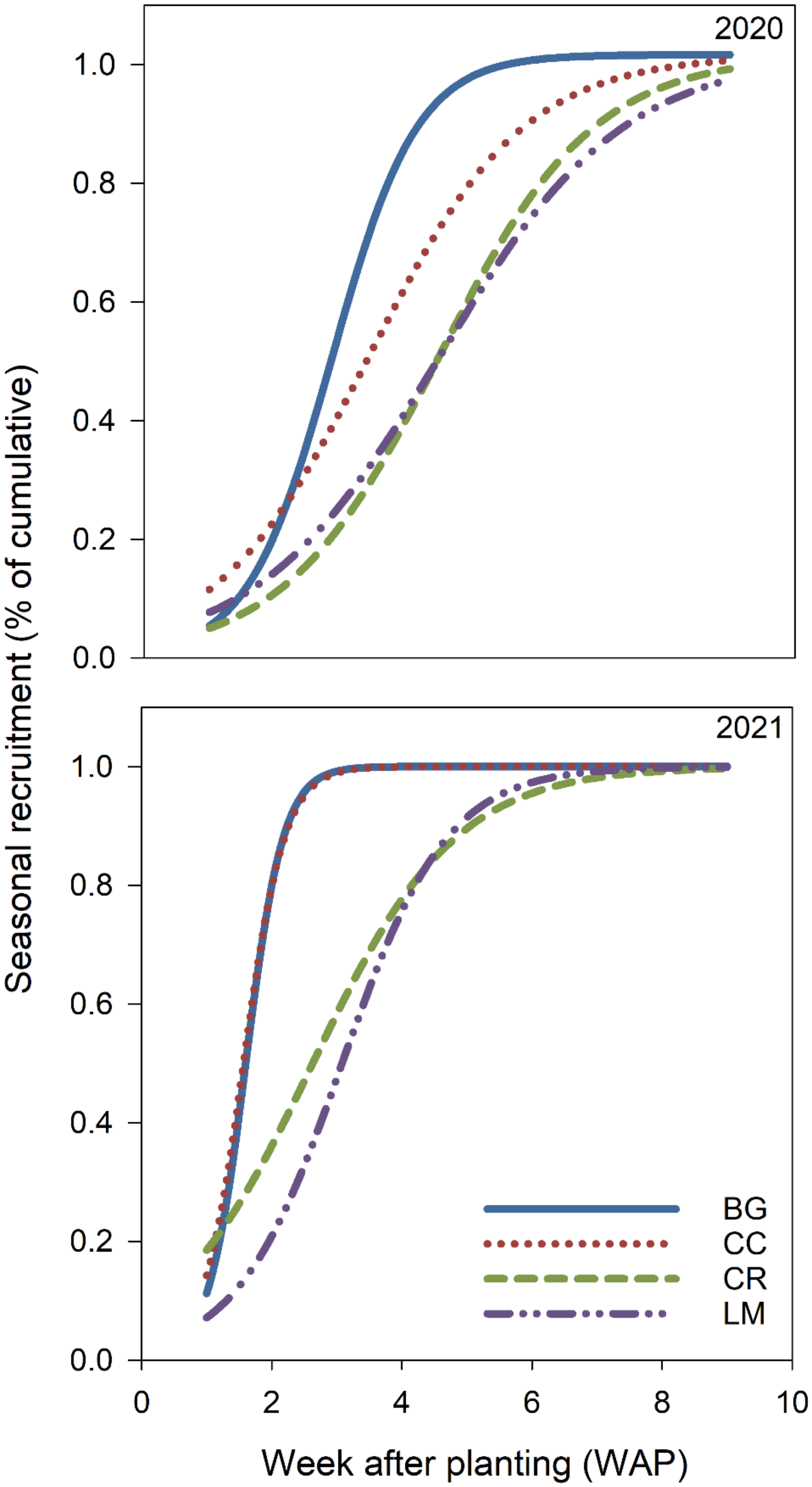
Fig. 3.1. Light transmission values (% reaching soil surface) for bare ground (BG), crimson clover (CC), cereal rye (CR) and living mulch (LM) treatments in 2020 and 2021. Relative transmission percentages were calculated based on equation 3 and are detailed in the methods section. Standard error bars were calculated for the mean for each treatment, at each WAP. Where standard error bars overlap along x- and y-axis treatments are not significantly; Tukey's HSD ($\alpha = 0.05$).

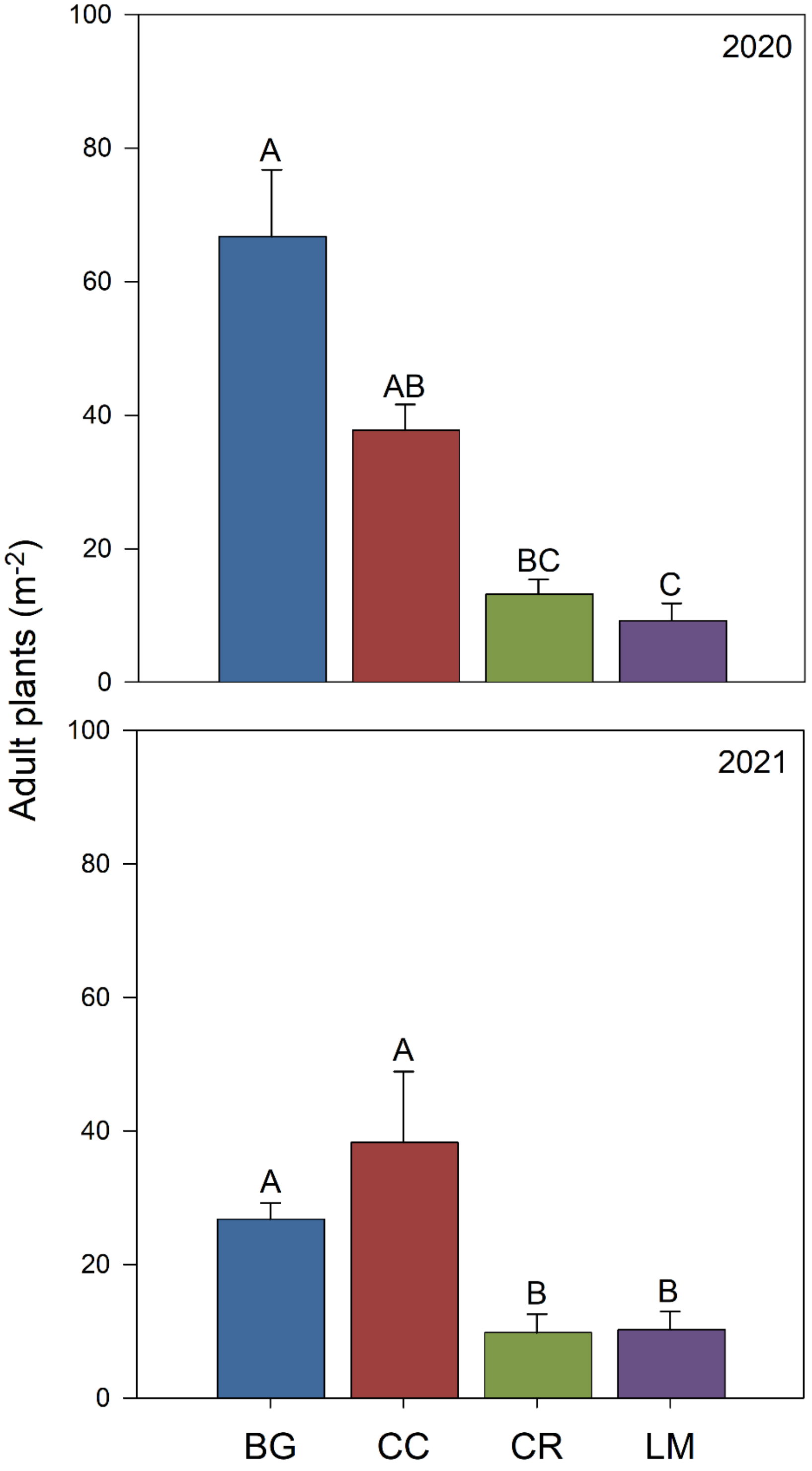
Fig. 3.2. Seasonal recruitment rates for bare ground (BG), crimson clover (CC), cereal rye (CR) and living mulch (LM) treatments in 2020 and 2021. Model parameters for each treatment, in each year, are based on equation 4 and are presented in Table 4.

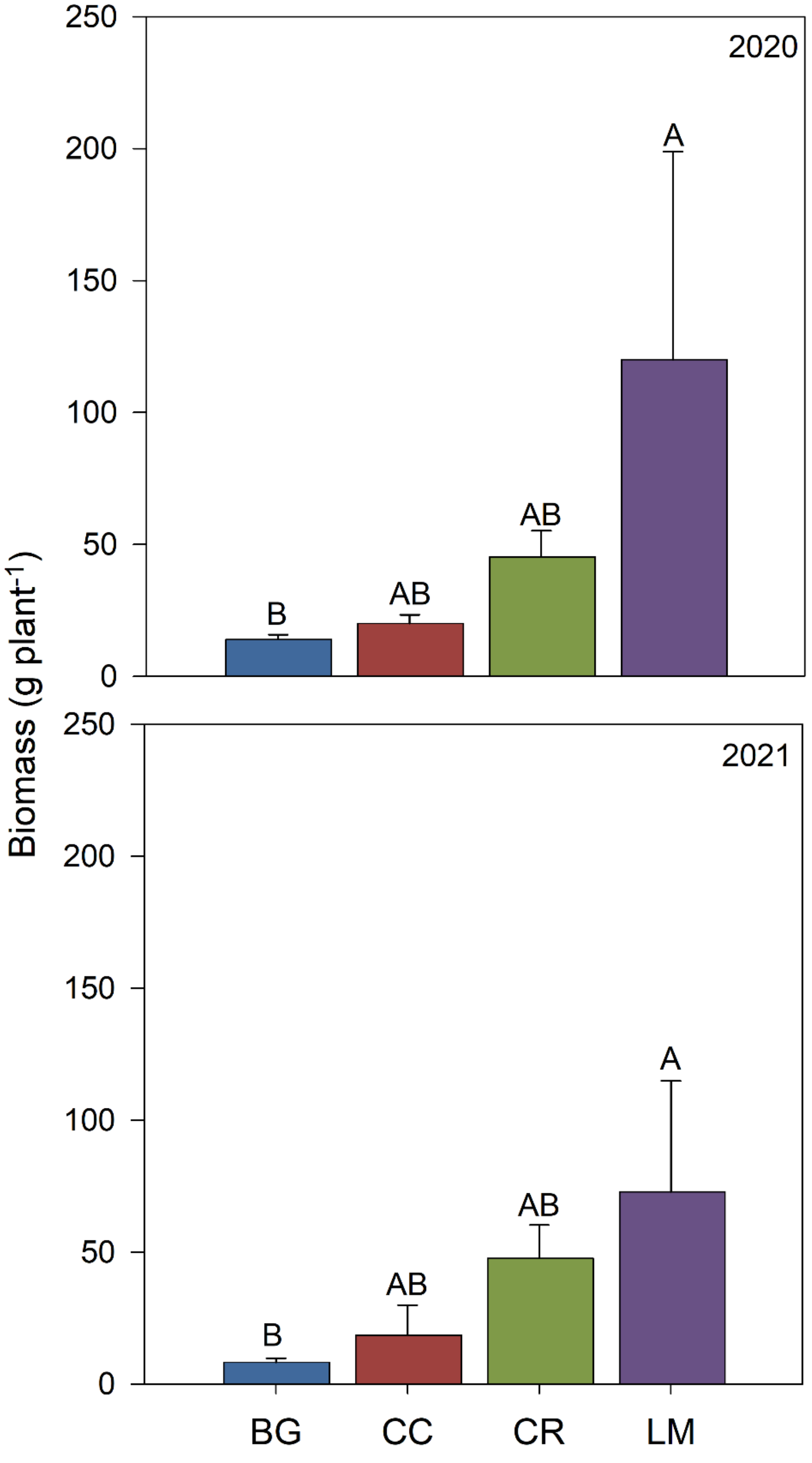
Fig. 3.3. Adult plant density (m^{-2}) bare ground (BG), crimson clover (CC), cereal rye (CR) and living mulch (LM) treatments in 2020 and 2021. Standard error bars were calculated for the mean for each treatment. Mean values with the same letter are not significantly; Tukey's HSD ($\alpha = 0.05$).

Fig. 3.4. Biomass (g $plant^{-1}$) for bare ground (BG), crimson clover (CC), cereal rye (CR) and living mulch (LM) treatments in 2020 and 2021. Standard error bars were calculated for the mean for each treatment. Mean values with the same letter are not significantly; Tukey's HSD ($\alpha = 0.05$).


100
80
60
40
20
0
2020
100
80
60
40
20
0
2021
Light transmission (% reaching soil surface)
1
3
5
7
9
Week after planting (WAP)
BG
CC
CR
LM


2020
2021
Seasonal recruitment (% of cumulative)
0.0
0.2
0.4
0.6
0.8
1.0
Week after planting (WAP)
0
2
4
6
8
10
BG
CC
CR
LM


2020
2021
Adult plants (m^{-2})
100
80
60
40
20
0
A
AB
BC
C
A
A
B
B
BG
CC
CR
LM



Biomass (g plant^{-1})
2020
2021
0
50
100
150
200
250
B
AB
AB
A
BG
CC
CR
LM

CHAPTER 4

CHEMICAL, ECOLOGICAL…OTHER? IDENTIFYING PERSPECTIVES ON WEED MANAGEMENT IN THE GEORGIA COASTAL PLAIN[1]

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[1] Weisberger, D., Ray, M., Rieber, L., Basinger, N.T. and J.J. Thompson. To be submitted to *Agriculture and Human Values*.

Abstract

Since the introduction and widespread adoption of chemical herbicides, weed management has become almost synonymous with herbicide management. Over-reliance on herbicide and herbicide resistant crops has given rise to herbicide resistant weeds, such as Palmer amaranth. Integrated weed management (IWM) suggests a combination of chemical-technological, mechanical-physical, and biological-cultural strategies to mitigate the risk and persistence of herbicide resistance, yet adoption of IWM has largely stalled. Research that aims to understand how and why IWM practices are or are not adopted have focused on single stakeholder groups such as farmers, but weed management decision-making often occurs within a social ecosystem where farmers, public sector (extension services) and private sector (agrichemical consultants) stakeholders co-create knowledge and practices. This study utilized Q-methodology to identify and describe the perspectives that exist within these social ecosystems, using a purposive sample of farmers, public and private sector employees across the state of Georgia, USA. We centered our investigations around the management of Palmer amaranth, which provided an important entry point into broader conversations about trends in weed management and agriculture. Results from our analyses of management preferences for Palmer amaranth uncovered two distinct perspectives that reflect not just these preferences, but generalized worldviews on agriculture. The two perspectives diverged in their attitudes toward IWM, but widely agreed on many BMP for herbicide stewardship and the need to understand basic biological characteristics of Palmer amaranth. Building on this, while differences were evident between perspectives around views of technology and system management, similarities were identified around attitudes toward regulation and path dependence.

Introduction

Prior to the widespread use of herbicide, weeds were managed through a combination of cultural practices, such as diversified crop rotations, mechanical and physical practices, such as the use of equipment to cultivate the soil and hand weeding (Staver, 2001). Weeding was laborious and time consuming and early adopters of herbicide viewed them in a quasi-miraculous light (Zimdahl, 2010). Weeds were virtually eliminated from crop fields, labor and time constraints were drastically reduced, and crop yields were raised given the near total absence of weeds (Zimdahl, 2010). As a result of these incredible early gains in production efficiency and associated economic returns, weed management has become synonymous with herbicide use, and both public and private sector weed science has focused almost exclusively on the research, development, and promotion of herbicides and their associated technologies (Zimdahl, 2010; Shaner, 2014). To provide one example of this, all actively used herbicides currently on the market were developed during the 50-year period from just after WWII to the mid-1990s (Zimdahl, 2010; Shaner, 2014).

In many ways herbicide-based weed management reached its zenith with the development and release of herbicide resistant (HR) crops in the mid-1990s. The most successful initial HR crops were those engineered with resistance to the herbicide glyphosate, more commonly known as Roundup (Charles, 2001). Glyphosate was first synthesized in the early 1970s and was identified as a highly effective broad-spectrum herbicide with a relatively safe toxicological profile and limited environmental impacts (Duke and Powles 2008). Despite these qualities, because it effectively killed any plant it touched, glyphosate use was limited until crops were engineered with resistance to it. The first HR crop to be widely used was Roundup Ready cotton, and farmers in the Southeast United States were the first group to use this technological package (Charles, 2001; Vulchi et al. 2022).

HR cotton altered the production landscape of the Southeast (Green, 2015; Bonny, 2016). Even greater gains in labor efficiency and management simplicity were made, and the ability to spray a highly effective broad-spectrum herbicide directly on a cash crop also facilitated an increase in conservation tillage practices throughout the region (Dill et al. 2008). However, a long-understood and predictable evolutionary outcome of relying exclusively on herbicides to manage weeds is the selection of herbicide resistance within populations of weed species (Menalled et al. 2016, Neve 2007, Neve et al. 2014). The rate of selecting for herbicide resistant weeds is expedited when few or only one herbicide is used continuously (Menalled et al. 2016, Neve et al. 2014, Norsworthy et al. 2012). An analog in medicine and human health has been the over-prescription and -use of limited antibiotic types and the development of bacteria that can no longer be treated with those commonly prescribed antibiotics (Beckie et al. 2021; Haywood et al. 2021).

In a very literal sense, the use of glyphosate was over-prescribed and -used, particularly by cotton farmers in the Southeast, US, where it displaced the use other herbicides and was used repeatedly on mono-cropped cotton (Norsworthy et al.; 2012; Kniss, 2018). Unsurprisingly, resistant weeds became commonplace, and one in particular, Palmer amaranth, has dominated the landscape ever since, shaping farmer practices, research directions, and industry sales (Ward et al. 2013; Roberts and Florentine, 2021). A native to the Southwest, US, Palmer amaranth is one of several “pigweed” (*Amaranthus*) species (Ward et al. 2013). It has become the driver weed throughout the Southeast, US, and has expanded into other parts of the US, as well as other cropping systems around the world (Roberts and Florentine, 2021). While Palmer amaranth possesses unique biological and genetic characteristics that make it a highly competitive and fecund species, it was not a weed of major concern until the HR crop era (Webster and Sosnoskie 2010).

The origin story of Palmer amaranth can be traced back to a farm field in Macon, County, Georgia (US) where the first case of glyphosate resistant Palmer amaranth was confirmed in the mid-2000s (Culpepper et al. 2006; Bétrisey, Boisvert and Sumberg, 2021). As more cases appeared, the reality of managing Palmer amaranth became stark; in many areas, crop yields were drastically reduced or unharvestable due to extensive infestations of this weed resulting in a dire economic situation for farmers in the state (Culpepper et al. 2010). Initial recommendations included a return to tillage (to bury weed seed), and an intensification of hand-weeding and herbicide-use; all of which were reverse many of the production efficiency, economic, and soil conservation gains that had accrued through conservation tillage (Price et al. 2011; Sosnoskie and Culpepper, 2014).

Subsequent management recommendations for Palmer amaranth have centered around the rotation and mixing of different herbicide modes of action (MOA) (Chahal et al. 2016).This has been bolstered by the release of newer HR crops, several of which have been engineered with resistance to the auxin herbicides, 2,4-D and Dicamba (Vulchi al. 2022). These were among the first synthesized herbicides, and are known for their ability to volatilize and drift onto non-target vegetation (Bish et al., 2021). Even in small quantities, these herbicides can damage non-HR crops and landscape plants, which has led to social and economic tensions within rural communities (Bish et al., 2021). Furthermore, Palmer amaranth with resistance to these herbicides had been empirically predicted and then confirmed only several years into the release of HR crops resistant to auxin herbicides (Tehranchian et al. 2017; Kumar et al. 2019).

Integrated weed management and social-processes

Although weed management since WWII has been defined primarily by herbicide management, calls for a more diverse set of management practices have existed for some time (Zimdahl, 2010). The idea of integrated weed management (IWM) was formally defined in the late 1970's as the "*the deliberate selection, integration, and implementation of effective weed control measures with due consideration of economic, ecological, and sociological consequences*" (Buchanan, 1976, p. 166). From an ecological and evolutionary standpoint, a core principle of IWM is the planned integration of "effective weed control measures" to limit the selection pressure placed on weeds by any one practice (Liebman and Gallandt, 1997). "Effective weed control measures" include the use of herbicide, but also cultural practices such as crop rotation and cover crops, and also mechanical-physical practices such as cultivation and hand-weeding (Harker and O'Donovan 2013).

In the wake of challenges with herbicide resistant weeds in the HR crop era, IWM research has been steadily increasing and results have shown IWM systems to be highly effective in managing herbicide resistant weeds (Harker and O'Donovan, 2013; Owen et al. 2015). This has also been the case for Palmer amaranth in cotton production systems in the Southeast, where the integration of practices such as cover crops and semi-permanent pastures with herbicide-based management, and even strategic tillage, have been shown to be highly effective at suppressing Palmer amaranth, reducing the burden placed on herbicides, and lessening the probability of selecting for resistant individuals (Price et al. 2012, 2016; Leon et al. 2015; Leon and Wright, 2018; Hand et al. 2021).

Yet despite decades of research supporting its effectiveness, IWM has not been widely adopted by farmers (Swanton et al. 2008; Owen et al. 2015; Liebman et al. 2016). The reasons for this are myriad and complex. Key factors that have appeared to hinder adoption include a greater perception of economic and agronomic risk associated with IWM practices relative to the sole use of herbicide and a lack of economic incentives and industry support (Swanton et al. 2008; Owen et al. 2015; Liebman et al. 2016). From a research standpoint, the original IWM "directive" quoted above included language around socio-economic factors; however, its subsequent study has been focused primarily on ecological and agronomic questions (Jordan et al. 2016). More recently, greater disciplinary diversity, and a concerted effort to understand and involve stakeholders in decision-making processes, have been features of IWM "calls to action" (Jordan et al. 2016; Liebman et al. 2016; 2018).

While sociological research has examined weed management decision-making, much of this has focused on individual categories of stakeholders, specifically farmers or consultants from regional or multinational agrichemical companies (Dentzman et al. 2016, Ervin and Jussaume 2014, Frisvold et al. 2009, Jussaume et al. 2019, Riar et al. 2013). This work has been essential in clarifying management preferences and epistemological orientations. However, weed management decision-making also occurs within a social ecosystem where farmers, public sector (extension services) and private sector (agrichemical consultants) stakeholders co-create knowledge and practices in real time while negotiating interlocking agronomic, economic, environmental and regulatory constraints (Dentzman and Jussaume, 2017; O'Connell and Osmond, 2018; Jussaume et al. 2019). Understanding how and why IWM practices are or are not adopted requires research that identifies and describes distinct perspectives that exist within these social ecosystems.

We were interested in engaging with varied stakeholders involved in weed management in the Georgia Coastal Plain. This area consists of approximately 1.1 million hectares of agronomic row crops, such as cotton, peanut, and corn, as well as over 85 thousand hectares in horticultural crops including perennial crops, such as pecan and blueberry, in addition to annual crops, such as peppers, cucurbits and brassicas (NASS, 2021). The cumulative value of these products in 2021 was approximately three billion USD, emphasizing agriculture's importance to the state's economy (Georgia Farm Gate Value Report, 2020). Considering its history and outsized impact on weed management in the state, we centered our investigations around the management of Palmer amaranth, which provided an important entry point into broader conversations about trends in weed management and agriculture more broadly. We used Q-methodology (QM) to explore the following questions: (1) What distinct perspectives exist on the management of this weed, (2) which management practices are valued, and (3) to what degree are IWM approaches are even used? While QM has been used extensively within the field of agricultural sustainability (Sneegas et al. 2021), the novelty of this work is in its application to the field of weed management, for which this is the first case to our knowledge.

Methods

Q-methodology (QM): approach and applications

QM integrates approaches from quantitative and qualitative traditions, enabling researchers to systematically explore, define, and compare sets of subjectivities on a given topic area (Brown, 2019). QM involves a focused card sort activity (called a "Q-sort") in which a participant is asked to rank cards (called a "Q-set") containing statements about a certain subject along a grid (in our study, labeled -4 through +4) (Fig. 4.1). The goal of this is to indicate a relative preference for a collection of statements (Watts & Stenner, 2012). The sorting process is often coupled with the use of a survey and interview, allowing the researcher to collect relevant demographic data and ask clarifying questions about participants' selections and decision-making processes (Watts and Stenner, 2012). Because it is intended to evaluate and characterize participant subjectivity, QM involves a "refusal to fix or impose the meaning of the Q-set items in advance...they are presented to the participants in a potential malleable state," to which the participants will assign and expound their own meaning, causes, and judgements (Watts & Stenner, 2012, p. 74). QM has been used increasingly within the fields of rural sociology and agricultural sustainability management to examine topic areas that may be considered polarizing, charged, or particularly complex, which makes it a good fit for our research topic (Previte et al. 2007; Sneegas et al. 2021).

QM in this study

Our approach to QM in this study was informed by Watts and Stenner (2012), with insights from Sneegas et al., (2021) used to guide best management practices during conceptualization, implementation, analysis, and reporting. Our specific methodological steps and decisions are informed by those works, unless otherwise specified. QM employs a set of qualitative and quantitative procedures that can be described as: *Study development*, *Data collection*, and *Data analysis and factor interpretation*. Within these broader categories a series of methodological steps were deployed and will be discussed herein.

Study development

Participant selection and recruitment

An important goal in QM participant selection is strategic heterogeneity; selecting participants with varied viewpoints that reflect differences of interest based on *a priori* experience with the research topic. For this study, we followed a non-random, criterion-based sampling strategy (Creswell, 2007) based on identifying individuals representing different stakeholder types from a geographically diverse range. The state of Georgia (US) comprises of 159 county areas of varying size and geographical location (mean county area = 969 km^2), almost all of which are involved with some type of agriculture production. Our goal in sampling was to select counties based on the area of annual row-crops produced (cotton, corn, and peanut), and their position on a NE-SW gradient along which the majority of annual row-crops are produced. The rationale for using these criteria was based on the prevalence of Palmer amaranth within these production systems, and the goal of sampling from a diverse geographic range, which would also capture ancillary production systems such as livestock or horticulture that may alter weed management practices and recommendations.

Using county-level production statistics from the National Agricultural Statistics Service (NASS, 2018) we identified three, five-county areas in which annual row-crop production was extensive. This list was reduced based on advice from Extension administrators and other agronomists with survey experience at the University of Georgia (UGA). Prior to contacting potential participants, all methods and procedures outlined below were approved by the University of Georgia Institutional Review Board (IRB).

Ultimately, we directly contacted UGA Extension agents in 12 counties to assist with participant recruitment. Of the 12 we contacted, six county Extension agents expressed willingness to participate in the study and aid in recruitment. Within each county, our goal was to speak with three stakeholder groups: extension agents, farmers, and consultants from the agrichemical sector. Within the farmer stakeholder group, we were also interested in differences based on a farmer's receptivity to IWM practices, namely the active participation or lack thereof in cover cropping. We shared the study background and participant selection criteria with these extension agents, who then put us in contact with farmer and agrichemical stakeholders with whom they worked. In each county of these six counties, we spoke with 1) the county extension agent responsible for providing crop and weed management support, 2) two farmers, and 3) a consultant from an agrichemical company involved in providing crop and weed management support to farmers within the county. In total, we spoke with 23 participants over a period of two and a half years from six counties in the state. The one exception to our criteria occurred in a county where the extension agent had previous experience in the agrichemical sector and thus fulfilled two roles. All stakeholders were provided with a stipend for their involvement.

Concourse development and Q-set selection

Watts and Stenner (2012, p. 33) state that, "a concourse is to a Q-set what a population is to a sample". That is, we began by identifying a broad collection of terms, ideas, positions, or beliefs from which a smaller representative subset was extracted for use in our QM study. A literature search was conducted using both scientific and popular press sources to develop the concourse of statements. During the Spring of 2019, we used Google and Google Scholar search engine using the keywords "Palmer amaranth", "Palmer amaranth management" and "Palmer amaranth biocontrol" to identify an exhaustive list of topics and practices that have been or are currently being studied or used to manage this weed. Approximately 150 article titles were screened, and 60 read in-depth to inform the construction of a concourse of 40 statements relevant to our research questions.

The statements were further screened to avoid redundancy and enhance clarity. This process led to the selection of 24 representative statements for Q-set. This Q-set was piloted with 10 participants, including agronomic researchers, and weed science graduate students at the UGA. These participants were asked to sort this initial set of cards using a "condition of instruction," a standardized question that structures the sorting activity. In our study, the condition of instruction was, "_______ is essential to the ongoing management of Palmer amaranth." Based on feedback from this initial set of participants, we refined language in some of the Q-set statement cards. Our final list of statements in the Q-set were selected to represent knowledge categories that inform weed management. These were classified as biological-cultural (n = 10), chemical-technological (n = 9), and mechanical-physical (n = 5) (Table 4.1).

Survey and interview protocol development

While some QM studies adhere to participants only sorting statements, many use surveys prior to, and semi-structured interviews after participants have completed a Q-sort activity (Sneegas et al., 2019). We modelled much of our work on recent QM studies within agriculture that engaged with farmers and other agricultural stakeholders (Pereira et al. 2016; Alexander et al. 2018; Lehrer and Sneegas, 2018; Wijaya and Offermans, 2019). These studies used short surveys to capture participants' demographic and production information for subsequent analysis. The survey is provided within the appendices at the end of the paper (Appendix C). A post-sort interview protocol was developed to explore participants' viewpoints on statements from the Q-sort itself and broader issues around weed management. For the former, participants were asked to explain their rationale for the placement of the statement-cards ranked high or low (+4, +3, -4, -3) and to discuss any statement-cards that were surprising or confusing. For the latter, participants were prompted to share their thoughts on the following issues relative to weed management if they had not arisen during the Q-sort itself: barriers/challenges to adopting alternative practices, economics, herbicide resistance, information sources/trust, motivating factors, policy, and stewardship/responsibility (Appendix D).

Data collection

Two researchers participated in data collection for all 23 participants. A protocol was developed to guide data collection (Appendix D). Data collection began with participants signing an informed consent document (Appendix E). This was followed by the 12-question survey described above (Appendix C) and an open-ended question in which participants were asked to share general information about their background within agriculture and their profession. Following this, we explained the study background and the Q-sort process to participants. Both the size of the Q-sort grid, and the cards on which statements were written, were large with text written in a bolded font (card size approx. 5 cm^2). All statement cards were randomly assigned a numerical value from one to 24. Participants were asked to complete an initial sort of the 24 statement cards into three piles based on how much they agreed, disagreed, or were neutral about a given statement card using a sorting grid with only three larger columns (Appendix F).

Participants were then instructed to sort cards into a "forced" distribution grid ranging from -4 (most disagree) to +4 most agree (Fig. 4.1). During the sort, we asked participants to "think out loud" while sorting cards to provide insight into their decision-making process around both the statements themselves and their relative position on the Q-sort grid. When sorting was complete, participants were instructed to copy their Q-sorts onto a duplicate sheet of paper. Results were copied into an excel spreadsheet for subsequent analysis. After this, we conducted the post-sort interview described above (Appendix D). The entire process from survey through post-sort interview was audio recorded and transcribed with the consent of all participants. We initially conducted four sessions in person in February and March of 2020. Due to the COVID-19 pandemic, the remaining 19 sessions were conducted using Zoom while maintaining the same format described above i.e., physical sorting of cards received in the mail as opposed to the use of an online Q-sort tool. The entirety of the process consisted of approximately 40 hours of data collection, with a mean data collection time of approximately 90 minutes.

Data analysis and factor interpretation

All Q-sorts were analyzed using KADE, an open-source QM analysis software (Banasick 2019). Following analysis guidelines from Watts and Stenner (2012), correlations were calculated across all participant Q-sorts and eight unrotated factors were extracted using principal component analysis (PCA). Each factor represents a group of individual participants whose q-sort rankings are intercorrelated. We use “factor” when describing the data analysis process in this section, but will use “perspective” in the results, discussion, and conclusion below. A 2-factor model was selected based on visual determination of slope change using a scree plot visual diagnostic (Appendix G). This 2-factor model accounted for 62% of the total variance and produced no confounded Q-sorts. A varimax rotation was applied to the data, and participants were sorted into two different factors based on similar eigenvalue loadings. Results were visualized as composite or “idealized” Q-sorts (Appendix H). These idealized Q-sorts represent the weighted average sort of all participants loaded onto a specific factor. Statements whose idealized Q-sort rankings were statistically different between factors were determined at the $p < 0.01$ significance level (Table 4.2).

After the identification and selection of two factors in KADE, both survey data and interview transcripts were divided based on factor membership. Descriptive statistics were calculated for each factor from participant survey responses and are presented in Table 3. Participants' transcripts were analyzed using ATLAS.ti coding software and were organized by factor. The entirety of each transcript (from pre-sort survey through post-sort interview) was coded in an iterative process beginning with a first-cycle coding approach that can be described as "descriptive" or "deductive" (Saldaña, 2016). We used keywords from both the statement cards themselves to create 24 codes. These were used to identify and characterize both relevant quotations. A subset of these quotations was organized into a table so that each statement card had one to two demonstrative quotations associated with each factor (Appendix I). Two coders contributed to the selection of demonstrative quotations and the construction of the table. Second-cycle coding was used to index codes that emerged inductively from memos and discussion between coders during the first-cycle coding (Saldaña, 2016). Using insights from Braun et al., 2019, who provide a framework for conducting thematic analysis, our coding process led to the development of themes that helped to further enlighten the description and understanding of the factors. The goal of this analytical process was to generate interpretations of each factor through an integrated analysis of idealized q-sorts, participant transcripts, and survey data to develop a synthetic perspective represented by each factor.

Results

The two factors extracted from our analyses are presented individually as narrative descriptions, including themes specific to each perspective. This is followed by a description of similarities (from survey data), consensus statements and themes shared across both perspectives. While a common convention in QM studies is to name factors in a representative or evocative way, "Perspective 1" (P1) and "Perspective 2" (P2) were used followed by a quotation from an associated participant that succinctly captured the quality of each perspective. Statement cards associated with specific parts of the narrative descriptions below are presented in the following format (statement card number: relative ranking e.g., S1: +4). Idealized Q-sort placements, and the z-score variance between the two perspectives for each statement card is presented in Table 2; statement cards where perspectives differ significantly ($p < 0.01$) are noted by the presence of an asterisk. Values for z-score variances provide an idea of how "far apart" perspectives are relative to the placement of a given statement card. Survey data divided by perspective are presented in Table 4.3.

P1: "*Right now, what I'm doing is working.*" (n = 14)

Participants who made up P1 viewed agronomic efficiency and productivity as essential pathways to economic viability. Farming was seen as an increasingly challenging business where uncontrollable factors such as weather and market forces perpetuated a highly variable and stressful working environment. Management decisions, and particularly changes to management practice, were made on a yearly basis in careful consideration of factors such as cash rent, labor, seed, and agrichemicals, as well as sunk costs such as farm machinery and infrastructure. P1 comprised 83 percent of extension agents, 50 percent of farmers, and 60 percent of the total agrichemical consultants. Of the farmers who had been referred to us by extension for their lack of interest in cover crops, 83 percent ended up in P1. Sixty-five percent of eligible participants (extension and farmers) had received funding for research and/or use of cover crops. Seventy-nine percent of participants said that the presence of high-value specialty crops affected their management or recommendations for Palmer amaranth. Eighty-six percent of participants in P1 listed Palmer amaranth as their primary pest issue (Table 3.3).

In P1, managing Palmer amaranth was seen as one of many management challenges. Herbicide-centric management and, when possible, HR crop-herbicide packages were considered to be the most practical, effective, and economical methods to control Palmer amaranth (S3: +4, S9: +3, S18: +3, S24: +2). As one participant from P1 stated, “Herbicide is kind of how we deal with these things.” Those in P1 were cognizant of the potential benefits of biological-cultural practices, such as cover crops, but displayed greater hesitancy toward adopting alternative practices given the potential for increased management complexity (S13: -4, S12: -4, S8: -3, S2: -3). For example, pertaining to S12 (“Incorporating semi-permanent pastures and forages into rotations”), one participant stated, “I just don’t think that’s feasible with what we're trying to do. And so many producers this day and time do not have livestock in their mix. Fifty years ago, that might have been a good option, but not today.”

P1 also expressed mixed receptivity to cover crops (S10: +1). While recognizing the benefits of cover crops in suppressing Palmer amaranth, and those related to soil conservation, participants from P1 also made clear that, “there's also expenses associated with it.” Despite being ranked similarly, conservation tillage practices were seen as somewhat important (S20: +1), with participants stressing gains in fuel and labor efficiency, as much if not more than any potential improvements to weed management. Tillage (S23: 0, S17: 0), while placed in a neutral column, was considered an important option under worst-case scenarios such as herbicide resistant Palmer amaranth. Said one participant in P1, “When Roundup started failing us, we had to go back to the old, traditional plowing.”

P1 themes: techno-optimism, -dissonance, and the “management program”

P1 participants primarily exhibited faith in the ability of technological approaches to solve both current and future challenges with weed management, a perspective commonly associated with “techno-optimism” (Dentzman et al. 2016; Gardezi and Arbuckle, 2020). One participant stated that for Palmer amaranth, there would always be a need “…to have new technology as we fight that;” while another asserted that, “what we have on the market today will control Palmer amaranth.” Others mentioned an overall belief in the ongoing ability of both scientists to develop new products and Land Grant-based weed scientists to verify their efficacy, “I know how much science and research goes into developing a new product and it's tested by our specialists. If UGA backs it, then it's got to be a good product and they're having to constantly come up with new things, because there is so much resistance.”

However, many in P1 also recognized the inherent challenges with herbicide-centric management, including human error and carelessness, but saw no viable alternatives, a perspective known as “techno-dissonance” (Dentzman et al. 2016). One participant mentioned that “Somebody’s going to screw it up and start using a lower rate. That’s what worries the tar out of me is they’re going to start building resistance,” while another added that, “Everything evolves, everything changes, you know. We know that no matter how good a herbicide is now, that it is only going to last so long. We can protect it with management - try to extend its life…but eventually how long will it last?”

Following from this, P1 participants valued management simplicity and herbicide-centric approaches to weed management, regardless of potential pitfalls. Weed management was generally framed as a linear process. This was described by many as a “management program” where different herbicides had specific roles to accomplish, and were assembled in a logical order to balance effectiveness and cost. P1 participants spoke at greater length about spray equipment, herbicide types and herbicide management approaches, information which was readily available and shared among stakeholders on a regular basis through workshops, field days and one-on-one interactions. Given the potential for legal or financial challenges, participants were equally cognizant of externalities such as herbicide resistance and potential off-site movement of herbicides that could damage non-target crops.

P2: “*Some cover is good, more is better. Some tillage is bad, more is worse.*” (n = 9)

In contrast to P1, participants in P2 viewed the synergistic use of conservation tillage and cover crops as the pathway to agronomic and economic success. P2 participants spoke about the use of herbicide, but had an interest in reducing or complementing this with the practices mentioned above. While diversification strategies were viewed through agronomic and economic lenses, for some participants in P2, they were also seen through moral and aesthetic lenses. P2 comprised 17 percent of extension, 50 percent farmers and 40 percent of all agrichemical consultants. Eighty-three percent of farmers identified as “cover crop farmers” by extension ended up in P2. One-hundred percent of eligible participants (extension and farmers) had received funding for research and/or use of cover crops. Forty-five percent of participants said that the presence of high-value specialty crops affected their management or recommendations for Palmer amaranth. Sixty-six percent of participants reported Palmer amaranth as their primary pest issue (Table 3.3).

Dealing with Palmer amaranth was seen as one of several emergent properties of a farming system driven by tillage reduction and cover crop implementation (S10: +4, S20: +4). Many participants from P2 expressed as much—with one saying, “I don’t really know how to separate my using conservation tillage from the cover crops.” There was also more discussion around intensive cover crop management; said one participant, “We're taking care of our cover crop, treating it like a cash crop. We're able to get a ton of biomass…we're not giving the pigweed anywhere to go, anywhere to grow.” P2 participants viewed newer crop-herbicides packages as simply one practice, among many, to help manage Palmer amaranth (S3: +3). As one participant put it, “I think they're useful. I don’t think they're essential. I don’t think we have to rely on the auxin herbicides for good control. They're another good tool.” However, there was greater mention of herbicide reduction and an expression of reticence around its use. Said one participant from P2, “We have our current model. We need herbicide to kill the weeds. I mean, right now we have to have it, you know. I don't like that we have to have it, but we do…I personally don't want to have to continue to keep using herbicides for the rest of my life.” While 100% of participants used or advised the use of HR crops, statement cards related to this topic (HR crops) were viewed either neutrally or only slightly positive (S24: 0, S18: +1, S9: +1).

P2 statement cards related to tillage were among the most negatively placed (S23: -4; S17: -3). This was directly tied to soil-based improvements that participants felt they had made over a long period of conservation tillage implementation. As a participant from P2 stated, “I don't have any tillage equipment and I think it stirs up the seeds…it just busts up the soil profile. It just changes the soil structure. It undoes everything I ever did over the last 20 something years, so tillage is just plain not an option.”

P2 themes: techno-skepticism and cover crop multifunctionality

P2 participants recognized the importance of chemical-technological approaches, but questioned the extent to which they should be relied upon (*techno-skepticism*). In particular, the use of auxin herbicides (2,4-D and Dicamba) and crops engineered with resistance to them were viewed as something to be used infrequently, if at all. Some mentioned that these herbicides were, "…not to be used as your primary - you ought to have it under control before you have to use that." Another lamented that, "everybody's like… well you got to use that, and I'm like no, you don't…we have quite a few herbicides at our disposal to effectively use to fight Palmer. And that's always the first question. Not how do I control it, it's what do I spray." Another participant expressed the following:

> "I think that we should reduce our herbicide use when we're dependent upon certain things like Roundup, like the 2,4-D. You know just because we have it, and we can use it twice a year doesn't mean that we should… it's important that even though we have these things available to us - that we should reduce our uses of those technologies…"

This techno-skepticism was associated with a different notion of weed management. One participant put it this way, "I'll tell you that going forward, I don't think chemistry is going to be the answer…I think biological control of weeds is going to by far outweigh chemical/transgenic applications, because essentially, we're dangerously close to running out of new chemistry."

As mentioned, P2 was associated with a strong interest in cover crops, one that evolved as experience with this practice grew. For many in P2, cover crop use began as a remedy for a singular management challenge. One participant mentioned that "Resistant weed management was definitely a focal point in my passion to implement cover crops." However, participants shared that the multifunctionality of this practice was key to its continued use. One participant clearly framed this idea when talking about early experimentation with a specific cover crop species:

> "I found out inadvertently early on…that tropical legume sunn hemp from a clean start, a dead start, will outgrow and suppress the pigweed all by itself. At 60 days the cover crop will be eight feet tall and the pigweed, if a pigweed emerged and started to grow with it, would be completely shaded out, would never make seed, and never reproduce. In the same time frame you've already made 150 plus units of nitrogen with that Sun Hemp, so boy where's the loss in this equation. Weed suppression, complete suppression of resistant Palmer and 150 pounds of nitrogen, that opened my eyes pretty big."

However, the notion of the multifunctionality of cover crops extended beyond the agronomic or economic benefits into areas of family and rural livelihood, environmental stewardship, and even aesthetics. One participant shared that cover cropping was, "the best thing for the family farm, the best thing for the environment, the best thing for the family and the community" and followed this by saying:

"I love to see my children out picking flowers in a field or picking peas in a field of a cover crop …taking them to their grandparents, it's a thing of beauty." Yet another framed management practices in an almost moral light, "I take pride in being a good steward…it's an opportunity or privilege to do something good for the world by the way I farm."

Perspective similarities and consensus statements

Responses from our survey indicated that many participants from both perspective groups shared many demographic characteristics and perspectives (Table 3.3). These include mean participant age, years of work experience, perception of Palmer amaranth severity, experience using or recommending the use of HR crop-herbicide packages, perceptions of conservation tillage practices, and years of experience with cover crops. Given the contextual similarities across perspectives, both were experienced and knowledgeable around herbicide management for the crops with which they worked and the biology of Palmer amaranth. There was widespread consensus around the importance of statement cards that reflected agreed-upon best management practices (BMP) for managing both herbicide resistant Palmer amaranth and other weeds, more generally (Norsworthy et al., 2012). As such, half of the statement cards did not significantly differ in the idealized q-sort placement between perspectives (Table 4.2).

As mentioned, all participants had a strong working knowledge of the underlying growth and reproductive potential of Palmer amaranth (S16, +2 for P1 and P2). There was considerable emphasis on the importance of “understanding the enemy” in order to economically manage it and avoid dealing with herbicide resistance. One participant framed this clearly by stating, “You got to understand how weeds grow to start with…We need to think about the biology of the Palmer, the seed production and all that.” Given that most participants had experience dealing with herbicide resistance, measures to keep populations low or non-existent that relied on physically removing Palmer amaranth plants from crop fields (S5, +1, +2, P1 and P2 respectively), and along waterways and field borders (S7: +2, P1 and P2), were both ranked positively, if less important than other management practices. Participant statements about these practices reflected many of the same dilemmas—for example, “If there's five Pigweed in a 100-acre field, we’re going to walk that field and pull them out... from a resistance management standpoint, we want to keep the escapes out,” and “Managing Palmer populations on field borders and waterways…you know to keep clean and try to keep those from becoming a breeding patch.”

Participants from both perspectives spoke about how essential crop rotation (S15: +4, +3, P1 and P2, respectively) and the use of diverse herbicide MOA and tank mixes (S3: +4, +3, P1 and P2, respectively) were for managing Palmer and staving off herbicide resistance. Participants agreed that these practices were both incredibly important and inherently coupled. One participant stated that, “Having a diverse rotation…rotation is very, very key. Simply because in those rotations, there are different herbicides used in different crop systems,” Another echoed this by stating, “Rotating those herbicide modes of actions, it’s important in a system… to me those modes of action, they help prevent that resistance, because if one of them misses, the other one has an opportunity to get it, so hopefully you're killing that plant and keeping it from reproducing.” Beyond the consensus around the importance of using a diversity of herbicide MOA, there were also similarities across perspectives on the quantity and trajectory of herbicide use that was needed to manage Palmer amaranth. The placement of statement cards for increasing (S6) and decreasing (S21) herbicide use did not significantly differ across perspectives. Participants agreed that herbicide use needed to follow recommended rates and application timing; and that doing otherwise had already and would continue to lead to more resistant Palmer amaranth. One participant from P2 stated that, “I don’t think increased herbicide use is, I mean to me it goes with reducing herbicide use…when you need them, you need them and you need to use them right,” while a participant from P1 followed this when stating, “Increasing herbicide use and reducing herbicide use. Either one could lead to resistance. Like you don't use enough or if you use too much…”

Shared themes: Incentives, regulations, and path dependence

Participants across both perspectives were skeptical about the effectiveness of regulation in limiting "bad behavior" and incentivization in motivating adoption of biological-cultural practices, such as cover crops. While herbicide resistance and Palmer amaranth management were described in serious terms by all participants, there was a general view that these phenomena arose from individuals seeking to cut costs and "cut corners." Despite this, most participants shared the belief that regulatory efforts geared toward limitations on the use of certain herbicides were an ill-conceived, one-size-fits-all approach that would both reduce farmers' options for managing this weed and fail to account for farm-specific contextualities.

Although many participants expressed frustration with "bad actors" and mentioned the need for increased accountability in some form, most were unable to clearly articulate what this might look like. When talking about poor herbicide management, one farmer from P1 stated:

"I think that when you do find someone who is truly abusing it, and there are a few who are apparently, and I don't really know any personally…there needs to be a way to make that hurt a little more. You know, through regular -- and I'm not talking about necessarily fines or something, but it needs to be where they take it seriously. There are people who, just as with any industry who just don't seem to really care, you know."

Similar nuance arose when participants spoke about the role that incentives played in catalyzing the adoption CC. One participant from P2 shared:

"I think those incentives work and I think doing it that way works well. But it needs to be, I don't want to say policed, I don't want to say that…but if you're going to plant a cover, a rye cover, and get an incentive from NRCS…you need to have specific seeding rate. You need to have the appropriate termination date. And you need to indicate that you're willing to utilize a strip-till method of planting, or no-till method of planting into that cover. You with me? So there needs to be – it needs to be done right if you're going to do it."

Lastly, many participants commented on the idea of "path dependence or "lock-in." Path dependence can be understood as a phenomenon by which a specific technology receives continual investment and dynamic returns over time, becoming self-reinforcing and essentially "locking out" any potential alternative technology, even if an alternative would provide potentially superior results or reduce risk (Liebowitz and Margolis, 1995; Cowan and Gunby, 1996). Examples of path dependence within agricultural systems have been documented with respect to equipment, crop variety and pest-management choices (Cowan and Gumby, 1996; Wilson and Tisdell, 2001; Vanloqueren and Baret, 2009; Desquilbet et al. 2019). One participant touched on this indirectly when discussing how farm size interacted with the adoption of newer HR crops:

"The larger you are, the more monolithic you need to be…you can't really say hey let's try this over here or try this over here. And with the Dicamba or the auxins, once you're in that system… do I keep planting you know 20% non-Dicamba cotton when I'm having to spend a half a day to prepare to move back to that cotton, you know when I'm spraying and stuff."

Another participant alluded to lock-in explicitly when saying:

"We have a lot invested in the equipment that we have. We need to use that equipment, you know. As much as I hate to admit it, we're kind of locked in that system. Breaking away from the conventional, even though we're doing some unconventional things like no-till you know, breaking away from the conventional row crop system is really hard for me to do."

Discussion

Results from our analyses of management preferences for Palmer amaranth uncovered two distinct perspectives that reflect not just these preferences, but generalized worldviews on agriculture. As described above, perspectives diverged in their attitudes toward the three knowledge categories of weed management, but widely agreed on many BMP for herbicide stewardship and the need to understand basic biological characteristics of Palmer amaranth. Building on this, while differences were evident between perspectives around views of technology and system management, similarities were identified around attitudes toward regulation and path dependence.

While these are not an exhaustive representation of perspectives on integrated approaches to weed management, they do correspond to similar observations within the literature. For example, Dentzman and Jussaume (2017) commented on the association between a farming ideology based on constant vigilance of time/labor demands and production efficiency and a decreased appetite for IWM practices. This same ideology has been associated with increased techno-optimism and -dissonance, suggesting that stakeholders involved in perpetuating this model may struggle to believe in the possibility of alternative weed management systems, whether or not they have faith in the possibility or new chemical-technological advancements (Dentzman et al. 2016; Dentzman and Jussaume, 2017; Jussaume et al. 2019; Jussaume et al. 2021). Conversely, prior work on stakeholders with a strong interest in cover crops, conservation tillage, and a desire to further diversify cropping systems has shown strong evidence for a “systems-thinking” mentality that ascribes myriad agri-environmental and social benefits to the adoption of these practices (Arbuckle and Roesch-McNally, 2015; Rosenzweig et al. 2019; Church et al. 2020). More recently, the agronomic practices mentioned above have been identified under the rubric of “Regenerative Agriculture”, which purports benefits of this systems-level approach, and is highly disinclined to implement even strategic tillage operations (Dentzman and Burke, 2021; Giller et al. 2021).

The challenge and prospect of change

While our results have led us to the identification and description of two perspectives, this masks the reality behind their distribution at a larger scale. The approach and ideological orientations, expressed to a greater extent in P1, are representative of the dominant paradigm for weed management in both Georgia and the US. Even discussions around IWM practices were framed within the confines of an herbicide-centric paradigm. For example, while both perspectives highlighted the importance of crop rotation, much of this centered on its role in allowing for the use of a more diverse suite of herbicides. More so, even the notion of diversity was often limited to the inclusion of two rather than just one crop in a rotation—as is the case in Georgia, where diversification in most agricultural land devoted to the production of cotton describes the addition of peanut as a crop rotation partner.

While cover crops were the IWM practice most discussed and used by both perspectives, they were only present on approximately 12 percent of harvested cropland in the state as recently as 2017 (Wallander et al., 2021). Other IWM practices represented within our statement cards, such as the use of insects or fungi for biocontrol of Palmer amaranth, are presently under-developed or researched, and almost non-existent within contemporary cropping systems in the state. The reality of IWM practices on the ground is that few are implemented and, those that are, are sparsely practiced.

Given the systemic challenges associated with the transition to IWM systems, and described by the participants from each perspective, we call attention to the role of policy governing the use of cover crops, specifically. We highlight both policy challenges that may contribute to the low adoption rates and perceptions of cover crops as an IWM strategy as well as an example of policy currently implemented that may provide a "way forward." Our discussion of cover crop policy is based on a variety of factors, including the results of our study itself, and their place as the most widely-used conservation practice within agronomic row crop systems in the US after conservation tillage. This relative ubiquity is associated with a proportionate investment from federal and state governments and reflects aspirations of wide-spread adoption given their relative ease of implementation and potential agronomic, as well as environmental, benefits (Bergtold et al. 2019; Prokopy et al. 2019; Basche et al. 2020; Park et al. 2022).

Primary expenses associated with cover crops are tied to seed and planting costs (Bergtold et al. 2019). Cost share options to offset these expenses are offered through the USDA NRCS via the Conservation Stewardship Program (CSP) and the Environmental Quality Incentives Program (EQIP) (Bergtold et al. 2019; Basche et al. 2020; Park et al. 2022). While almost all participants across both perspectives had at least some experience with cover crops, fewer eligible P1 participants had received funding for cover crop use or even expressed an interest in doing so. This may be explained partially by the influence of policy-factors on behavior.

Firstly, funding options and amounts vary by state and county and are also subject to changes in state and federal policy over time (Bergtold et al. 2019, Basche et al. 2020). Cost-share amounts in certain years may be a catalyst for participation in these programs, and a disincentive in others (Bergtold et al. 2019; Thompson et al. 2022). Secondly, CSP and EQIP differ in their requirements, goals and associated technical support (Bergtold et al. 2019; Basche et al., 2020; Park et al., 2022). One analysis of program effects on conservation practice adoption within the Corn Belt region of the US showed that mismatches between farmer goals and cost-share programs have been shown to reduce the area planted to cover crops (Park et al. 2022). Indeed, early bad experiences with these programs, and poor communication among farmers and NRCS staff, may stifle future participation (Wardropper et al. 2022). Thirdly, while cost-share payments within programs vary based on a set of farm-level and demographic factors, the actual outcomes of conservation practices are poorly documented, which may lead to negative perceptions about their use, specifically, and about federal and state governments, generally (Bergtold et al. 2019; Basche et al. 2020; Prokopy et al. 2019).

Clearly, it is crucially important to maintain consistent federal and state funding for these programs, as well as clear lines of communication between farmers and NRCS personnel around goals and program specifics. Recent reviews of policy and sociological factors on conservation program adoption and use substantiate this point using examples from a litany case studies in the US (Bergtold et al. 2019, Prokopy et al. 2019). However, it is equally important to ensure that those receiving cost-share payments are also subject to some form of accountability. One clear example that avoids overly punitive measures is the tiered-cost-share payment approach currently utilized in the state of Maryland. In the 2022-2023 growing season, any farmer participating in a cover crop cost-share program receives a base rate ($45), this can be doubled ($90) if combined with practices such as no-till and drill-seeding, as well as early planting and later termination (Maryland Department of Agriculture, 2022). This highly incentivizes practices that would contribute positively to IWM efforts, and necessitates careful documentation of practices, planting, and termination dates by farmers in order to maximize incentives.

In the specific case of using cover crops for IWM, meta-analyses in both the Midwest and Southeast have consistently shown that cover crop biomass quantity strongly correlated with weed suppression, which is directly tied to earlier planting and later termination dates (Nichols et al. 2020; Weisberger et al. 2022) Additionally, having a reasonable base cost-share payment for those who may not be ready from either a structural or even personal level to optimize cover crop biomass may help retain farmers who might otherwise opt out of these programs after the expiration of the funding period (Wardropper et al. 2022). This has been highly effective in increasing both rates of adoption and the percentage of harvested crop land using cover crops in Maryland, and has been supported by a commensurate amount in state funding for these programs (Wallander et al. 2021).

Conclusion

We used QM to identify and describe shared perceptions of agricultural systems, farmer livelihoods, and sustainability among row-crop stakeholders in the state of Georgia. These perceptions emerged through a facilitated dialogue in which participants shared their thoughts on the relative merits of practices to manage the problematic weed, Palmer amaranth. Given the inherent parameters imposed by our statement-cards, as well as the game-like nature of the card sort, we believe that QM was a highly effective tool in encouraging a safe space for researcher-participant interaction, which lead to a productive and enjoyable research process for agricultural stakeholders. QM has considerable utility for work on human dimensions research in agriculture, particularly where interactions among varied stakeholder motivations and worldviews shape both farming practices and the landscape itself. In our case specifically, QM allowed us to identify and holistically describe perspectives that contribute to a greater understanding of the factors that influence stakeholder decision-making and how they envision the ongoing challenge of farming and managing weeds. Moving from a description of stakeholder perspectives to actionable steps to catalyze the adoption of greater IWM is extremely challenging. A body of literature, and now the results presented in this study, characterize the degree to which systemic factors shape stakeholder perceptions and practices. Given this, our research approach was carefully considered to work with varied stakeholders across farming, public and private sectors, as these collectively shape what farming practices look like in real time. Addressing the complex, "economic, ecological, and sociological consequences" of weed management will similarly entail a collective effort shared by members of the groups discussed above, and increasingly the public at large, to influence policy and practice.

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Table 4.1. Knowledge categories pertaining to weed management and the associated Q-set statements from this study.

Category	Statement (card number)
Biological-cultural	• Using higher crop seeding rates (2)
	• Relying on pathogens to kill Palmer plants and seeds (8)
	• Using cover crops (10)
	• Incorporating semi-permanent pastures and forages into rotations (12)
	• Relying on insects and rodents to eat Palmer plants and seeds (13)
	• Growing more than two crops at the same time (intercropping) (14)
	• Having a diverse cash crop rotation (15)
	• Understanding how Palmer grows and reproduces (16)
	• Adopting narrow row spacing (19)
	• Using conservation tillage (20)
Chemical-technological	• Relying on Roundup (1)
	• Rotating herbicide MOAs and using tank mixes (3)
	• Using technologies like drones (4)
	• Increasing herbicide use (6)
	• Using current transgenic crops and herbicides (9)
	• Keeping herbicide use constant (11)
	• Having access to new transgenic crops and herbicide packages (18)
	• Reducing herbicide use (21)
	• Relying on auxin herbicides (2,4-D and dicamba (24)
Mechanical-physical	• Hand-weeding (5)
	• Managing Palmer populations on field borders and waterways (7)
	• Using secondary tillage (mechanical cultivation) (17)
	• Washing harvest equipment and tires to limit Palmer seed movement (22)
	• Using primary tillage (23)

Table 4.2. Idealized Q-sort rankings for each statement card and perspective. Statement cards are presented in descending order relative to the inter-factor z-score variance. Differences between factors are indicated by "*" which represent thresholds of $p < 0.01$. Consensus and disagreement statement cards are separated by horizontal line.

Statement	Perspective 1	Perspective 2	Z-score variance
Using primary tillage (plowing, disking etc.)*	0	-4	0.976
Using secondary tillage (mechanical cultivation)*	0	-3	0.537
Incorporating semi-permanent pastures and forages into rotations*	-4	0	0.462
Using cover crops*	1	4	0.450
Using higher crop seeding rates*	-3	0	0.398
Using conservation tillage (no-till or strip-till)*	1	4	0.367
Relying on pathogens to kill Palmer plants and seeds*	-3	0	0.350
Relying on auxin herbicides (2,4-D and dicamba) *	2	0	0.267
Using current transgenic crops and herbicides*	3	1	0.212
Having access to new transgenic crops and herbicide packages*	3	1	0.211
Relying on Roundup*	-2	-4	0.144
Relying on insects and rodents to eat Palmer plants and seeds*	-4	-2	0.088
Washing harvest equipment and tires to limit Palmer seed movement	0	-1	0.075
Hand-weeding	1	2	0.069
Keeping herbicide use constant	-1	1	0.056
Rotating herbicide MOAs and using tank-mixes	4	3	0.053
Having a diverse cash crop rotation	4	3	0.014
Using technologies like drones	-1	-1	0.013
Growing more than two crops at a time (intercropping)	-2	-2	0.009
Reducing herbicide use	-2	-2	0.006
Increasing herbicide use	-1	-3	0.005
Adopting narrow row spacing in crop production	0	-1	0.004
Managing Palmer populations on field borders and waterways	2	2	0.003
Understanding how Palmer grows and reproduces	2	2	0.002

Table 4.3. Descriptive statistics for each perspective (P1 and P2) based on survey questions. See Appendix C for survey document.

	P1	P2
Sample size	N = 14	N = 9
Stakeholder composition (% of total extension/farmer/consultant)	83/50/60	17/50/40
Average age (years)	44.5	45.6
Farm size (ha)[a]	528	564
% Land owned[a]	52.6	46
Experience (years)	19	20
Diversity of management experience[b]	2.5	2.0
Specialty crop presence affects weed management (% yes)	79	45
Palmer severity rating (1-10)[c]	7.8	7.8
Palmer primary pest (% yes)	86	66
Experience with herbicide resistant Palmer (% yes)	79	100
Experience with auxin crop-herbicide packages (% yes)	93	100
Conservation tillage receptivity (1-10)[d]	8.0	8.0
Cover crop experience (years)	11.5	12.7
% Eligible participants that have received funding for cover crops[e]	65	100

[a] Values for farm size and ownership represent those from farmers only.

[b] Participants had 4 operation categories from which to choose: Row crops, pastured livestock, horticultural crops, and timber crops. Least diverse to most diverse experience values range from 1 to 4.

[c] Higher values indicate greater perception of Palmer severity.

[d] Higher values indicate greater receptivity to conservation tillage practices.

[e] Mean values calculated based on farmer and extension stakeholders only. Industry representatives not involved in state funded cover crop research and/or use (sample sizes, P1 [n = 11] and P2 [n = 7])

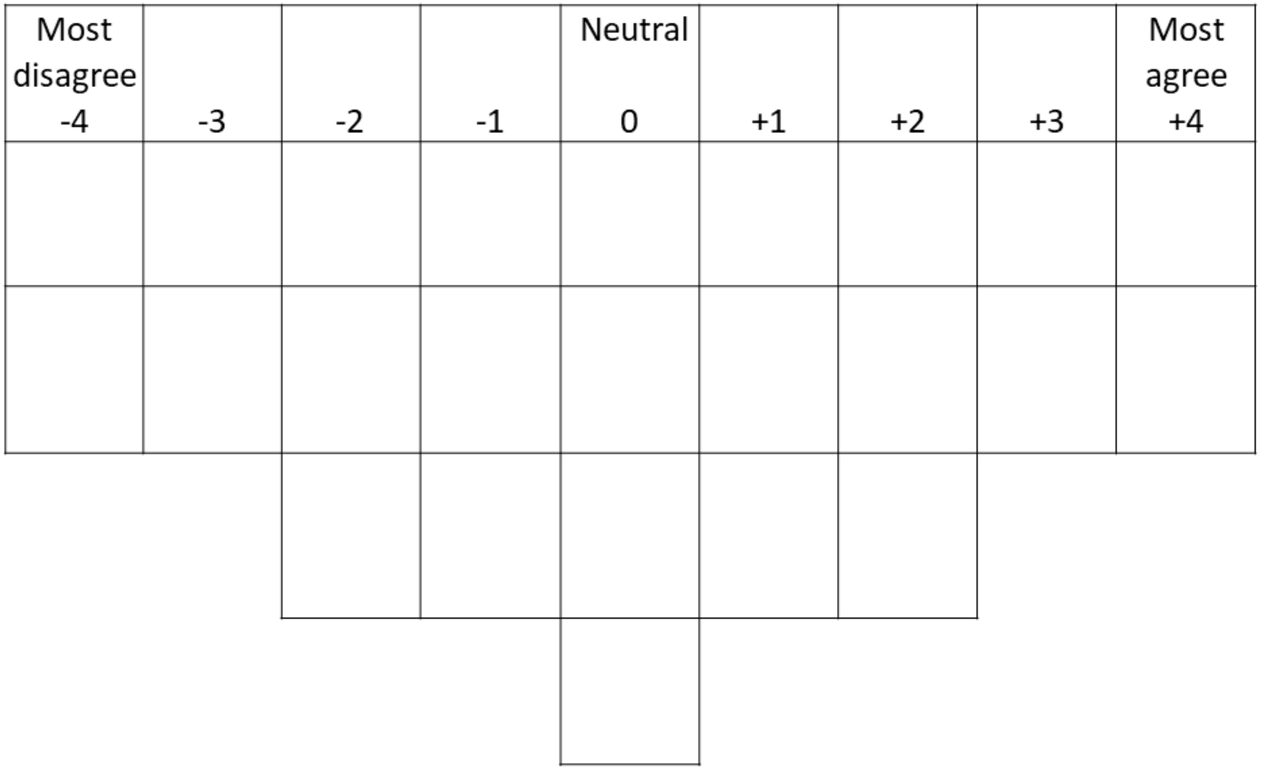


Fig. 4.1. Q-sort grid used by participants.

CHAPTER 5

CONCLUSION

Results from the biophysical research described above are clear. Annual cover crops (CC) and the perennial white clover species used as a living mulch in the studies described in this work were highly effective at reducing the abundance of weed seedlings that emerge (are recruited) from the soil weed seed bank. The suppressive effect of both is linked to the quantity of biomass produced by annual CC or the persistence of living vegetative biomass that remains via the living mulch species used in our experiment. CC biomass quantity and persistence are inherently tied to reductions in the quantity of light that reaches the soil surface. While we could not account for light reductions in our meta-analysis data, annual cover crop biomass was the significant factor to emerge from our analysis and light reduction was a key correlate tied to the suppression of weed seedling recruitment in our field study in Georgia. This is an important factor in limiting weed seedling recruitment in the Southeast, where Palmer amaranth, which has a light requirement for germination, is the driver species in agronomic systems.

However, given the relative heat and humidity of the region and commensurate increases in rates of cover crop residue degradation, relative reductions in weed seedling recruitment may be nullified over the course of the growing season. Weed biomass accumulation of surviving plants may be optimized under situations where few individuals remain (i.e., intraspecific competition reduced) and resources may be greater (i.e., moisture and nutrient provisioning from

CC). This phenomenon highlights the challenge in managing highly plastic weed species with high rates of fecundity, and the importance of zero-weed thresholds.

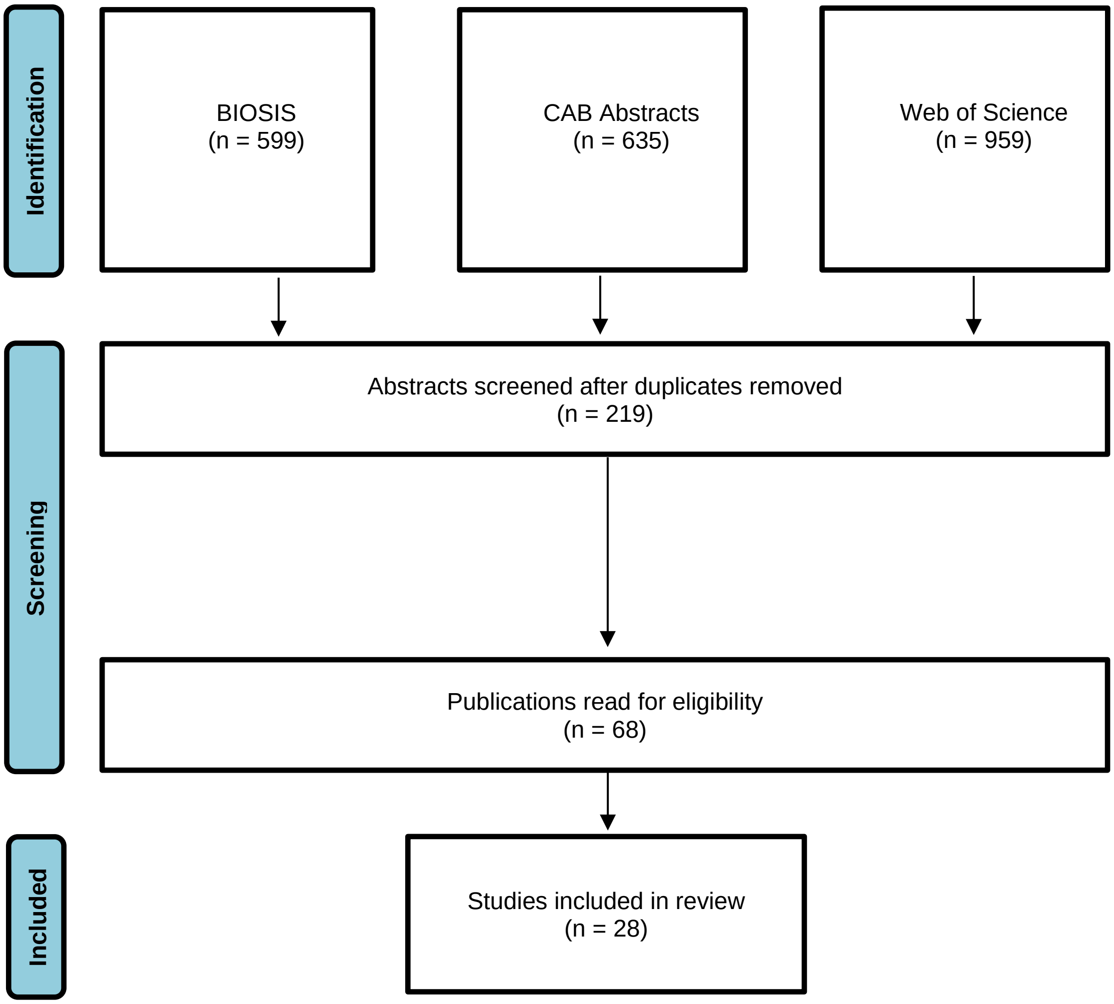
Further work exploring herbicide-CC synergies, and novel integration of plant hormones, residual herbicide, and CC, is necessary to reduce weed seedling recruitment levels even further. However, the necessity of physical removal of escapes cannot be overstated. While economically burdensome, hand-weeding will remain a critical aspect of integrated weed management for species such as Palmer amaranth. Advances in intelligent sprayers and robotics may alter the potential for managing surviving weeds, but are presently still under development and may be economically untenable technologies for a large subset of agronomic crop producers in the region in both the short- and long-term future.

From a sociological perspective, our study was not designed to determine the extent of integrated IWM practices. We did find that stakeholder motivations may have much to do with inherent belief systems and worldviews. This suggests, and is bolstered by CC adoption rate data for example, that IWM practices may remain limited to small groups of farmers that are highly motivated by non-economic in addition to economic factors. Consequently, the presence of highly attractive incentive programs coupled with educational resources and requisite monitoring would be vital to increasing cover crop adoption and forwarding this form of IWM. However, challenges remain, as much of the funding and resource allocation related to conservation programs, and extension and research budgets, is determined at levels beyond which the stakeholders we spoke with have any substantial effect. This policy disconnect is not unique to Georgia, but points to both the importance and difficulty of engagement across scales to achieve sustainability goals within agriculture broadly.

From an agronomic and weed science perspective, research tied to both earlier annual cover crop establishment and later termination methods is needed. This is particularly true given the economic conditions and insurance instruments that encourage farmers to optimize cash crop yield by planting longer season varieties. The use of perennial living mulches does present a hopeful novel pathway for crop production and weed suppression in the region, but is confined to areas and production systems where irrigation is present. Their adoption will also require an even greater change in management mentality in addition to alterations to current equipment. The inclusion of living mulch management programs into conservation policies such as EQIP or CSP would further catalyze their adoption. However, verifying the positive findings of perennial living mulch systems at the plot-scale under real-world conditions will be crucial to elucidating trade-offs and to promoting an honest depiction as a viable alternative management strategy.

Lastly, social science research that engages directly with stakeholders and allows them to co-create data and knowledge is not only important in generating useful data, but engenders a positive attitude and creates the potential for collaborative networks among diverse sets of stakeholders. This human element, the ability to conversate, to share ideas and reflections should not be underestimated or overlooked. This is particularly true when trying to understand the challenge of change and encourage the adoption of alternative strategies in the face of myriad and diverse biophysical and socioeconomic challenges.

Appendix A. Prisma diagram detailing literature search.



Appendix B. List of 28 publications included in meta-analysis.

Aulakh J, Price A, Enloe S, Wehtje G, Patterson M (2013) Integrated Palmer Amaranth Management in Glufosinate-Resistant Cotton: II. Primary, Secondary and Conservation Tillage. Agronomy 3:28–42

Aulakh JS, Price AJ, Enloe SF, Van Santen E, Wehtje G, Patterson MG (2012) Integrated Palmer Amaranth Management in Glufosinate-Resistant Cotton: I. Soil-Inversion, High-Residue Cover Crops and Herbicide Regimes. Agronomy 2:295–311

Brown SM, Whitwell T (1985) Weed Control Programs for Minimum-Tillage Cotton (Gossypium hirsutum). Weed Sci 33:843–847

DeVore JD, Norsworthy JK, Brye KR (2012) Influence of Deep Tillage and a Rye Cover Crop on Glyphosate-Resistant Palmer Amaranth (Amaranthus palmeri) Emergence in Cotton . Weed Technol 26:832–838

DeVore JD, Norsworthy JK, Brye KR (2013) Influence of Deep Tillage, a Rye Cover Crop, and Various Soybean Production Systems on Palmer Amaranth Emergence in Soybean. Weed Technol 27:263–270

Hand LC, Nichols RL, Webster TM, Stanley Culpepper A (2019) Cereal rye cover crop and herbicide application method affect cotton stand, Palmer amaranth (Amaranthus palmeri) control, and cotton yield. Weed Technol 33:794–799

Koger CH, Reddy KN (2005) Effects of Hairy Vetch (Vicia villosa) Cover Crop and Banded Herbicides on Weeds, Grain Yield, and Economic Returns in Corn (Zea mays). J Sustain Agric 26:107–124

Koger CH, Reddy KN, Shaw DR (2002) Effects of rye cover crop residue and herbicides on weed control in narrow and wide row soybean planting systems. Weed Biol Manag 2:216–224

Lassiter BR, Jordan DL, Wilkerson GG, Shew BB, Brandenburg RL (2011) Influence of Cover Crops on Weed Management in Strip Tillage Peanut. Weed Technol 25:568–573

Malik MS, Norsworthy JK, Culpepper AS, Riley MB, Bridges W (2008) Use of Wild Radish (Raphanus raphanistrum) and Rye Cover Crops for Weed Suppression in Sweet Corn . Weed Sci 56:588–595

Norsworthy JK, Frederick JR (2005) Integrated weed management strategies for maize (Zea mays) production on the southeastern coastal plains of North America. Crop Prot 24:119–126

Norsworthy JK, Korres NE, Walsh MJ, Powles SB (2016) Integrating Herbicide Programs with Harvest Weed Seed Control and Other Fall Management Practices for the Control of Glyphosate-Resistant Palmer Amaranth (Amaranthus palmeri). Weed Sci 64:540–550

Palhano MG, Norsworthy JK, Barber T (2018) Cover Crops Suppression of Palmer Amaranth (Amaranthus palmeri) in Cotton. Weed Technol 32:60–65

Price AJ, Balkcom KS, Duzy LM, Kelton JA (2012) Herbicide and Cover Crop Residue Integration for Amaranthus Control in Conservation Agriculture Cotton and Implications for Resistance Management . Weed Technol 26:490–498

Price AJ, Monks CD, Culpepper AS, Duzy LM, Kelton JA, Marshall MW, Steckel LE, Sosnoskie LM, Nichols RL (2016) High-residue cover crops alone or with strategic tillage to manage glyphosate-resistant Palmer amaranth (Amaranthus palmeri) in southeastern cotton (Gossypium hirsutum). J Soil Water Conserv 71:1–11

REDDY KN (2003) Impact of Rye Cover Crop and Herbicides on Weeds, Yield, and Net Return in Narrow-Row Transgenic and Conventional Soybean (Glycine max) 1. Weed Technol 17:28–35

Reddy KN, Koger CH (2004) Live and Killed Hairy Vetch Cover Crop Effects on Weeds and Yield in Glyphosate-Resistant Corn. Weed Technol 18:835–840

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Sci 51:987–994

Reddy Krishna N (2001) Effects of Cereal and Legume Cover Crop Residues on Weeds , Yield , and Net Return in Soybean (Glycine max) Author (s): Krishna N . Reddy Published by : Cambridge University Press on behalf of the Weed Science Society of America Stable URL : https://w. Weed Technol 15:660–668

Smith AN, Reberg-Horton SC, Place GT, Meijer AD, Arellano C, Mueller JP (2011) Rolled Rye Mulch for Weed Suppression in Organic No-Tillage Soybeans. Weed Sci 59:224–231

Timper P, Davis RF, Webster TM, Brenneman TB, Meyer SLF, Zasada IA, Cai G, Rice CP (2011) Response of root-knot nematodes and Palmer amaranth to tillage and rye green manure. Agron J 103:813–821

Vann RA, Reberg-Horton SC, Edmisten KL, York AC (2018) Implications of cereal rye/crimson clover management for conventional and organic cotton producers. Agron J 110:621–631

Webster TM, Scully BT, Grey TL, Culpepper AS (2013) Winter cover crops influence Amaranthus palmeri establishment. Crop Prot 52:130–135

Wells MS, Reberg-Horton SC, Mirsky SB (2016b) Planting date impacts on soil water management, plant growth, and weeds in cover-crop-based no-till corn production. Agron J 108:162–170

Wells MS, Reberg-Horton SC, Smith AN, Grossman JM (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. Agron J 105:539–545

Wiggins MS, Hayes RM, Nichols RL, Steckel LE (2017) Cover Crop and Postemergence Herbicide Integration for Palmer amaranth Control in Cotton. Weed Technol 31:348–355

Yenish JP, Worsham AD, York AC (1996) Cover Crops for Herbicide Replacement in No-tillage Corn (Zea mays). Weed Technol 10:815–821

Zotarelli L, Avila L, Scholberg JMS, Alves BJR (2009) Benefits of vetch and rye cover crops to sweet corn under no-tillage. Agron J 101:252–260

Appendix C. Survey administered to all study participants.

Date: __________________

Participant ID: __________________

Please check the appropriate box or provide information that best describes your current situation.

1. What is your gender?

Male	Female

2. What is your age?

____

3. What is your role? *Please check under the box that best applies.*

Extension agent	Farmer	Sales representative

If you are a **farmer**, approximately how many acres do you rent _____________ vs. own _______________

4. How long have you worked in your current role?

____

5. With which of the following types of production do you work?

Row crops	Horticultural crops	Pastured livestock	Timber crops

6. Does the presence of high-value specialty crops near areas you farm affect your weed management decisions/recommendations?

YES	NO

7. On a scale from 1-10, how problematic would you say Palmer amaranth is? (Either on your farm or for farmers with which you work).

8. Is Palmer amaranth the primary pest issue you deal with?

YES	NO

If **NO**, what is the primary pest issue you deal with?

____

9. Has herbicide resistant Palmer amaranth been an issue you've faced or seen?

YES	NO

10. Are you currently using, or advising the use of Xtendflex or Enlist crops and herbicides to manage Palmer amaranth (e.g., Fexapan, Xtendimax, Enlist One, Enlist Duo, Engenia)?

YES	NO

11. On scale from 1-10, how would you rate your investment/interest in conservation tillage?

12. Do you have experience working with cover crops?

YES	NO

If **YES**, how many years of experience do you have using cover crops?

____

If **YES**, are you currently or have you received either state or federal funds to support cover crop use or research?

YES	NO

Appendix D. Study protocol

INTRODUCTIONS & PRIMER

I. Introduction to the project
II. Informed consent
III. Survey
IV. Primer questions
    1. *Can you tell me a little about your background, how you came to be in your position (as a farmer, extension agent, industry rep)?*

Q SORT

I. Q instructions
    1. From your packet, take out the small envelope that says "cards" and the stapled set of documents (these contained written instructions for everything we'll be doing)
    2. From the gut sort (*p.2*)
    3. From your packet, take out the header. Grid sort, agree > disagree > neutral, think-out-loud (*p.3*)
    4. Response entry, will scan and send to us after (*p.4*)

II. Sort-specific questions
    1. *Could you say a bit more about why you placed those statements with the most* ***positive ratings*** *of +4 or +3?*
    2. *Could you say a bit more about why you placed those statements with the most* ***negative ratings*** *of -4 or -3?*

3. *Were there any cards that **surprised or confused** you? Why?*

POST-SORT INTERVIEW

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1. Has herbicide resistance been an issue you've dealt with?
    a. What do you see as the major causes of herbicide resistant Palmer?
    b. Where/to whom do you go to for advice/information about managing this weed?
    c. *What role, if any, do you see for government interventions/policy? **incentives / regulations**?*
2. Is there anything else you would like to discuss?

WRAP-UP

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1. Docs to scan/photo and send
2. Checks
3. Additional interview contacts (farmers, industry)

TOPICAL CHECKLIST

☐ Herbicide Resistance

☐ Policy/regulation

☐ Economics

☐ Information sources/trust

☐ Stewardship/responsibility

☐ Motivating factors

☐ Barriers/challenges

Appendix E. Informed consent document signed by all participants prior to study participation.

UNIVERSITY OF GEORGIA
CONSENT FORM
EVALUATING STAKEHOLDER PERSPECTIVES ON PALMER AMARANTH MANAGEMENT IN GEORGIA

You are being asked to take part in a research study. The information in this form will help you decide if you want to be in the study. Please ask the researcher(s) below if there is anything that is not clear or if you need more information.

Principal Investigator:	Dr. Jennifer Jo Thompson Crop and Soil Sciences jjthomp@uga.edu	**Co-Investigator:**	David Weisberger Crop and Soil Sciences dweis@uga.edu

We are doing this research study to learn more about farmer, extension agent, and industry sales representative perspectives on managing Palmer amaranth. You are being invited to be in this research study because you are a farmer, extension agent, or agricultural industry sales representative that has experience with Palmer amaranth.

If you agree to participate in this study:

- We will ask you to participate in an interactive interview process. This will be audio recorded.
- The process should take 60-90 minutes.

Participation is voluntary. You can refuse to take part or stop at any time without penalty. If there are questions that make you uncomfortable, you can skip these questions if you do not wish to answer them.

Your responses may help us understand stakeholder perspectives on the management of Palmer amaranth, this may help inform extension and outreach approaches, and provide information to better manage this weed.

We will take steps to protect your privacy, but there is a small risk that your information could be accidentally disclosed to people not connected to the research. To reduce this risk we will not use your name or any identifying information when collecting or analyzing data. We will collect basic information from you as well in order to dispense the participant collaboration stipend of $100.

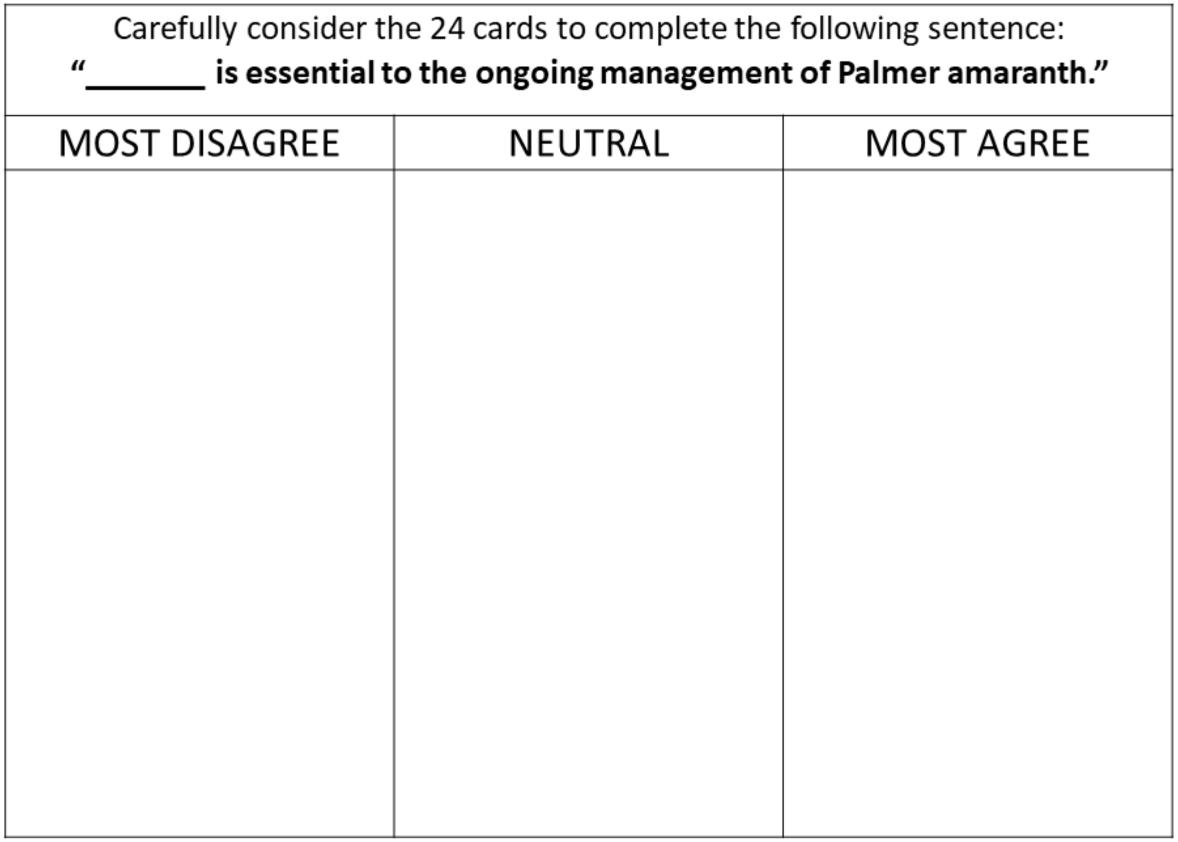
Please feel free to ask questions about this research at any time. You can contact the Principal Investigator, Dr. Thompson at 706-410-1921, *jjthomp@uga.edu*. If you have any complaints or questions about your rights as a research volunteer, contact the IRB at 706-542-3199 or by email at IRB@uga.edu.

If you agree to participate in this research study, please sign below:

____________________ Name of Researcher	____________________ Signature	________ Date
____________________ Name of Participant	____________________ Signature	________ Date

Please keep one copy and return the signed copy to the researcher.

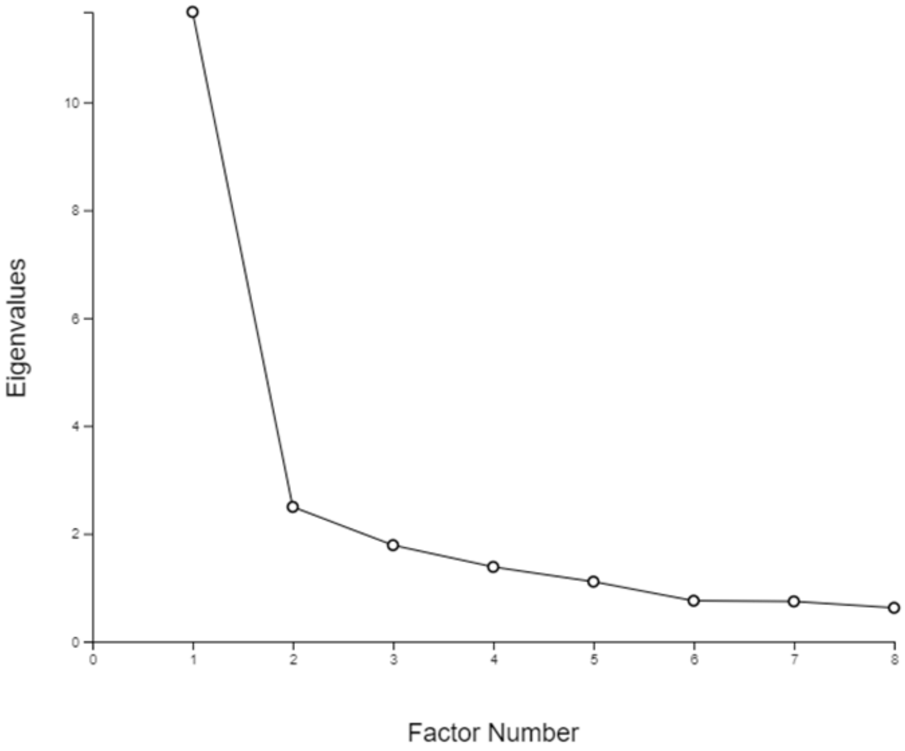
Appendix F. 4. Initial Q-sort grid.



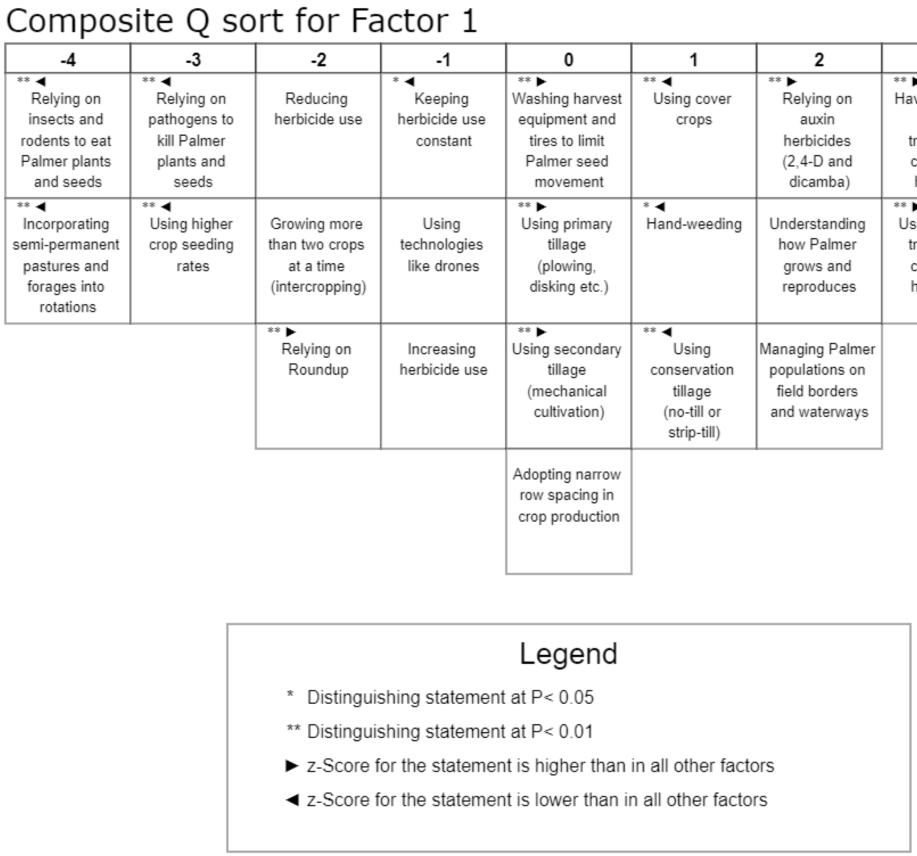
Carefully consider the 24 cards to complete the following sentence:
“_______ is essential to the ongoing management of Palmer amaranth.”

MOST DISAGREE	NEUTRAL	MOST AGREE

Appendix G. Scree plot displaying eigenvalues on the y-axis and factor number on the x-axis.



Appendix H. Idealized (“Composite”) Q-sorts for perspectives (factors) one and two, respectively.

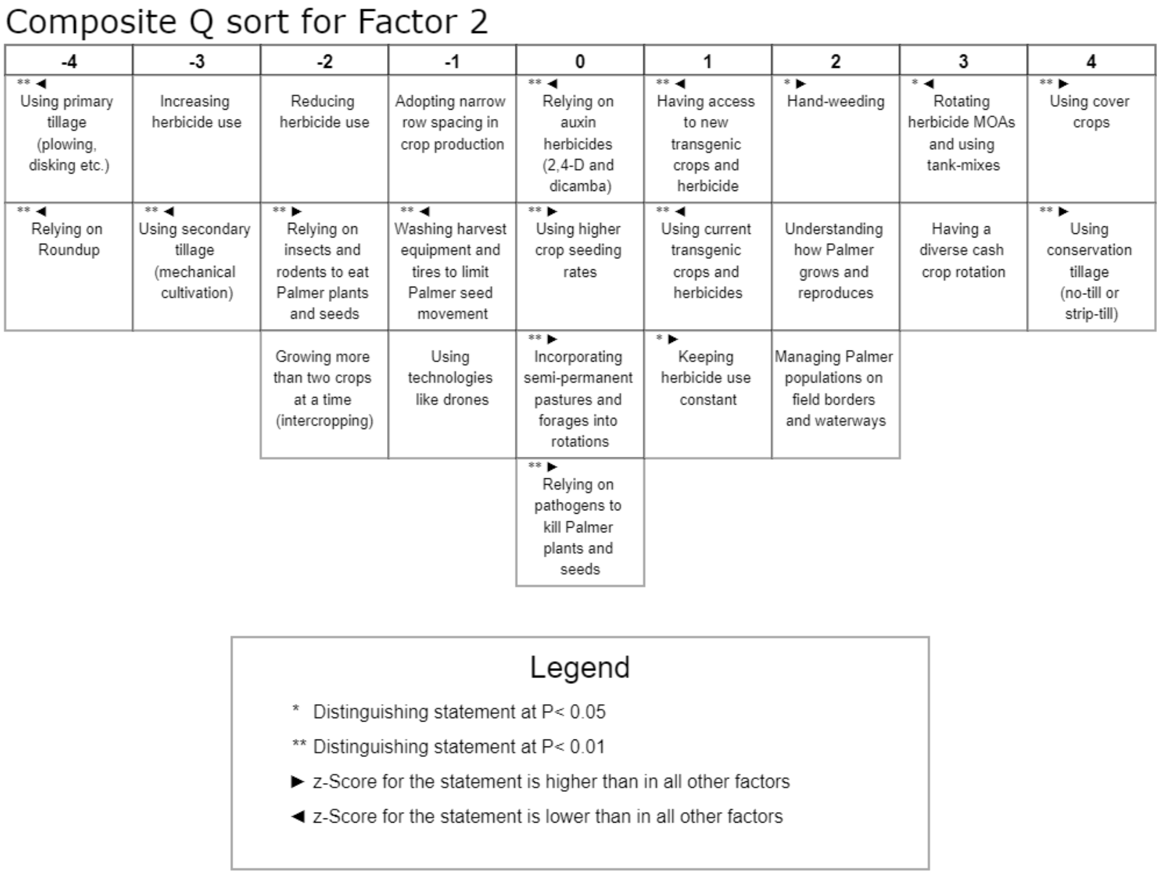


Composite Q sort for Factor 1

-4	-3	-2	-1	0	1	2	3	4
** ◀ Relying on insects and rodents to eat Palmer plants and seeds	** ◀ Relying on pathogens to kill Palmer plants and seeds	Reducing herbicide use	* ◀ Keeping herbicide use constant	** ▶ Washing harvest equipment and tires to limit Palmer seed movement	** ◀ Using cover crops	** ▶ Relying on auxin herbicides (2,4-D and dicamba)	** ▶ Having access to new transgenic crops and herbicide	* ▶ Rotating herbicide MOAs and using tank-mixes
** ◀ Incorporating semi-permanent pastures and forages into rotations	** ◀ Using higher crop seeding rates	Growing more than two crops at a time (intercropping)	Using technologies like drones	** ▶ Using primary tillage (plowing, disking etc.)	* ◀ Hand-weeding	Understanding how Palmer grows and reproduces	** ▶ Using current transgenic crops and herbicides	Having a diverse cash crop rotation
		** ▶ Relying on Roundup	Increasing herbicide use	** ▶ Using secondary tillage (mechanical cultivation)	** ◀ Using conservation tillage (no-till or strip-till)	Managing Palmer populations on field borders and waterways		
				Adopting narrow row spacing in crop production				

Legend

- * Distinguishing statement at P< 0.05
- ** Distinguishing statement at P< 0.01
- ▶ z-Score for the statement is higher than in all other factors
- ◀ z-Score for the statement is lower than in all other factors



Composite Q sort for Factor 2

-4	-3	-2	-1	0	1	2	3	4
** ◄ Using primary tillage (plowing, disking etc.)	Increasing herbicide use	Reducing herbicide use	Adopting narrow row spacing in crop production	** ◄ Relying on auxin herbicides (2,4-D and dicamba)	** ◄ Having access to new transgenic crops and herbicide	* ► Hand-weeding	* ◄ Rotating herbicide MOAs and using tank-mixes	** ► Using cover crops
** ◄ Relying on Roundup	** ◄ Using secondary tillage (mechanical cultivation)	** ► Relying on insects and rodents to eat Palmer plants and seeds	** ◄ Washing harvest equipment and tires to limit Palmer seed movement	** ► Using higher crop seeding rates	** ◄ Using current transgenic crops and herbicides	Understanding how Palmer grows and reproduces	Having a diverse cash crop rotation	** ► Using conservation tillage (no-till or strip-till)
		Growing more than two crops at a time (intercropping)	Using technologies like drones	** ► Incorporating semi-permanent pastures and forages into rotations	* ► Keeping herbicide use constant	Managing Palmer populations on field borders and waterways		
				** ► Relying on pathogens to kill Palmer plants and seeds				

Legend

* Distinguishing statement at P< 0.05
** Distinguishing statement at P< 0.01
► z-Score for the statement is higher than in all other factors
◄ z-Score for the statement is lower than in all other factors

Appendix I. Exemplary quotations from first cycle coding for both perspectives.

Statement card	Perspective 1	Perspective 2
1. Relying on Roundup	p16: But it's not for pigweed control, because pretty much, and I mean I think just about every population -- we're going to have glyphosate resistant pigweed in every field at this point. So the Roundup is a tank mix partner, or for other weeds. I mean it's still a good herbicide, it's just not good for Palmer.	p6: Roundup is reaching a point where it's not doing a great -- it's not doing anything on Palmer. And it doesn't seem to me that it's as good on other weeds anymore either. I think we got to definitely get away from relying on Roundup.
2. Using higher crop seeding rates	p3: I can't see using a higher crop seeding rate because there's a point of diminishing returns and there's no need to put all the corn –- if you put 38,000 plants of corn in a single row, you're not going to make anything. They turn into weeds on each other....You're not accomplishing anything, to me, on that.	p12: …running up the seeding rates, even though it can be a benefit in terms of having the plant you want out there and providing shade... all my thinking on this is devoted towards Palmer amaranth...and that's why I'm saying having the shade out there. All that could be could be a benefit, but it comes at a high price.
3. Rotating herbicide MOAs and using tank-mixes	p3: And to me that's where the next one comes in, rotating those herbicide mode of actions, it's important in a system. And then using tank mixes to prevent resistance from occurring in other chemistries and to help… to me those modes of action, they help prevent that resistance, because if one of them misses, the other one has an opportunity to get it, so hopefully you're killing that plant and keeping it from reproducing. So to me those are the two that I most agree with.	p22: I think that's a really big deal. You don't want to lean on one product too heavy, so if you mix MOA's or tank mix partners you're spreading the risk basically and keeping resistance from building to that technology.
4. Using technology like drones	p5: I'm going to go with using technologies like drones because I don't know how drones help with weed management… like drones are for you to see I guess what's already out there. And in my opinion, you should be knowing what's out there and already taking the steps to reduce those weeds. I mean most farmers know these fields. They know what grows there. They know what weed problems they have. And a lot of people can't afford to have drones, so I just don't feel like that's a good one.	p21: Again, something I don't know about would be the using technology with drones. I'm sure there's stuff coming, but that's just something that I'm kind of neutral on.

5. Hand-weeding	p9: Hand weeding is very effective. It is… It's also kind of expensive. And sometimes labor is very difficult to get there in a timely manner.	p2: …if there's five Pigweed in a 100-acre field, we're going to walk that field and pull them out...and carry them out, because we do not want ever to, just from a resistance management standpoint, we want to keep the escapees out.
6. Increasing herbicide use	p20: I don't think increasing herbicide use is going to help us. All that's going to do is cost us money, okay. Plus all that's going to do is if you overuse it, then we're going to get into a situation of, the Palmer could become resistant to it, you know.	p1: I don't think increased herbicide use is, I mean to me it goes with reducing herbicide use. That's not – when you need them, you need them and you need to use them right. When you don't need an herbicide, don't use it.
7. Managing Palmer populations on field borders and waterways	p9: I say managing Palmer populations on field borders and waterways. I guess that's saying that even though you're not spraying that boundary and you're not utilizing it -- I guess I would call that roads and ditches, I guess waterways -- you know to keep clean and you know we tried to keep those from becoming a breeding patch, I guess.	p19: Number seven would be the next one, managing Palmer population on field borders and waterways. If you let one weed go to seed, you've got several hundred thousand seeds that you're going to fight for another year.
8. Relying on pathogens to kill Palmer plants and seeds	p9: You know, I guess considering you know, at the rate that pigweed produces seeds and that it grows, that it would be – you would have to wait on something detrimental to wipe it out. It wipes out the whole pigweed crop, it's probably going to wipe out my whole crop too.)	p6: Relying on pathogens to kill Palmer plants. I don't have much experience with that.
9. Using current transgenic crops and herbicides	p9: We don't need to come back down on using 2,4-D and Dicamba and some of these technologies. We kind of need to keep going in the direction we're going. It's going to be hard to back down.	p1: I'm neutral on the current transgenic crops and herbicides. I think they're useful. I don't think they're essential. I don't think we have to rely on the auxin herbicides for good control. They're another good tool.
10. Using cover crops	p4: Cover crops are really -- that I see as an investment in your land, your operation. Yes, over the long-term it's going to build up the soil. There's all kind of benefits associated with it, but there's also expenses associated with it.	p6: ...we've reached a point where we're taking care of our cover crop and treating it like a cash crop, so we're able to get a ton of biomass, a ton of root restructure, and basically we're not giving the pigweed anywhere to go...anywhere to grow, you might say.
11. Keeping herbicide use constant	p13: Keeping herbicide use constant. You know, I don't look at it that way. I'm not trying to just keep it on constant. I'm going to use where I need it, when I need it. So I'd say minus two.	p12: Yeah, that was a tough one for me. We have our current model, we need an herbicide to kill the weeds. So, that -- it was just a tough one, you know. I mean, right now we have to have it. I don't like it that we have to have it, but we do so, you know, putting it in a negative two almost goes against where I've had herbicide in a positive category. But my

		reasoning behind having in the neutral is because I personally don't want to have to continue to keep using herbicides for the rest of my life.
12. Incorporating semi-permanent pastures and forages into rotations	p4: Incorporating semi-permanent pastures and forages in the rotation, I just don’t think that’s feasible with what we're trying to do. And so many producers this day and time do not have livestock in their mix. 50 years ago, that might have been a good option, but not today.	p12: …we're not like we were in the middle of the 20th century, where we have a little bit of a lot. You know, we have a lot of a little bit. And having livestock and having different crops is just not a place where we're at. Now we have a lot invested in the equipment that we have, so we need to use that equipment…as much as I hate to admit it, we're kind of locked in that system. And breaking away from the conventional, even though we're doing some unconventional things like no-till, breaking away from the conventional row crops system in today's time is really hard for me to do. Would like to be able to do it, we'd love to be able to do it, but doing it and doing it successfully, I think, is a -- it's a challenge
13. Relying on insects and rodents to eat Palmer plants and seeds	p16: …relying on insects and rodents, I don't know how much they would help the crowd. There probably is some of that. I mean I know we have insects that feed on the Palmer amaranth leaves but I don't know about seeds. And I don't -- I think even that feeding, it's not enough in most cases that I've seen to kill a plant or to keep it from producing seed.	p21: Relying on insects and rodents to eat Palmer plants and seeds...I don't know what -- that kind of comes out of left field for me in my thinking. Y'all need to have studies that show we can turn something loose, I don’t know.
14. Growing more than two crops at a time (intercropping)	p16: The next one, growing more than two crops at the same time, I don't think most growers are going to do that. I just don't think that's a good — some do that in certain cropping situations, but as far as the total of our acres it’s very minimal. I don't think it's an option that’s going to -- it's not going to help with pigweed control. It actually would make it worse because your herbicide options are more limited when you have two crops in the same field.	p12: It’s something I've done a lot of reading on. It would be really neat to be able to do that. And I'm just thinking in terms of growing cotton. You know, what other stuff could you have intercropping, and it'd be great to have something, but I don't know enough about it to do it. And it’d be great to do so, and if someone's doing it I'm sure they could educate us on it, but I’m going to put that in the negative one column.
15. Having a diverse cash crop rotation	p23: Having a diverse rotation. Rotation is key. Rotation is very, very key. Simply because in those rotations, there are different herbicides used in different crops systems.)	p1: My number threes, I would consider them equal… using cover crops and having a diverse cash crop rotation…we have guys that are very successful that are conventional tillage and they’ve done it that way for years. They truly understand Palmer. They understand modes of action. They're not scared to use hand-weeding if they get behind or whatever, but that crop rotation is still critical to them. Not only for maintaining your high yields, because you are shifting crops, but also it forces you on that mode of action thing, if you're in a different

		cash crop each year. So that’s one reason they're very successful, that rotation through crops, different herbicides. We have several herbicides that overlap each other or that can be used in multiple crops, so our successful guys are not using the same herbicide in multiple crops, if that makes sense.
16. Understanding how Palmer grows and reproduces	p16: I think, based on what, what I have experienced you know, working with growers, and I think a lot of growers now do understand how Palmer grows and reproduces because of over the last 15 years, what we have dealt with in managing this weed since the Roundup or the glyphosate resistance, so to me, they have to understand that to be able to do the things that they need to in in managing it and reducing the amount that they're dealing with from year to year.	p22: Understanding how Palmer grows and reproduces. That's with any disease, insect, weed. If you don’t -- the farmer doesn't understand how it gets there, or why it's there, or how their whatever MOA herbicide they use, how it works, I mean...you need to know why you're using something. So, I think that's a big deal, education. And they don't have to know the science, the molecules and all that, but they need to understand a little bit, how it works a pre-emerge versus a post-emerge and all that stuff.
17. Using secondary tillage (mechanical cultivation)	p16: The next one I had was number 17, using secondary tillage, and that's mechanical cultivation. I would say prior to resistance, that was, that would be here on the agree pile, but to me it's neutral, I mean it's not used much anymore because of the resistance issues... And a lot of those weeds, they come up in the row. What I’ve seen. They’ll come up anywhere, but the ones that are in the row you're not going to get with a cultivator or mechanical tillage. You may be able to get some of those that are in the middle, in the row middles, but you're not going to be eliminating the Palmer amaranth.	p22: …anywhere you turn dirt over it’s going to bring new viable weed to the top to germinate.
18. Having access to new transgenic crops and herbicide packages	p5: I know how much science and research goes into developing a new product, and it's tested by our specialists, and if UGA backs it, then it's got to be a good product. And they're having to constantly come up with new things, because there is so much resistance. So I think having access to those new things will help with the reduction of weeds, palmer amaranth.	p12: …it's important that even though we have these things available to us that we should reduce our uses of those technologies when we can.
19. Adopting narrow row spacing in crop production	p16: I think with our current systems our growers are -- they're not going to do that because of the cost of investing or changing equipment. And what we have works, so I just disagree with, I mean to me, we have a good system, farmers are used to the row pattern that they're doing. I’m not saying that that couldn’t help, but I don't think they're going to do it, so I don't think that it would, I just don't think	p15: I could see where that could be beneficial, but I would say that most farmers are set up to do things how they are, and they're not going to just do that to control Palmer.

	they would implement it.	
20. Using conservation tillage (no-till or strip-till)	p4: …yes I do support conservation tillage. Do I think it’s right in every place? No.	p19: I'm on board 100% with strip till, no-till, conservation, cover crop.
21. Reducing herbicide use	p16: That unusual. I’m just thinking about where we are currently with the systems that we have in place. I don't see too much -- and I just don’t think reducing herbicide usage is going to help us. I think that we're going to have to continue using the systems that we have in place now as long as they're available and can be, and if they add systems it’s fine, but I just don't know that we would be reducing herbicide usage.	p22: Yeah, I think you need to stay within the label, myself. I think if you go spraying too little is -- I mean spraying too much and spraying too little both can contribute to resistance.
22. Washing harvest equipment and tires to limit Palmer seed movement	p10: I've got washing the harvest equipment and the tires, I'm neutral on, because we have Palmer everywhere, so I'm just spreading Palmer back to Palmer. Now that's not to say I'm not interested. We wash out every morning, and we do all that, but we don't -- I'm kind of neutral on that.	p15: So the washing the equipment and tires and all that. You could do that, and it would help because you know you wouldn't be toting seed from place to place but I just don't see us taking the time or people taking the time to do that.
23. Using primary tillage (plowing, disking etc.)	p9: you know when Roundup started failing us, we had to go back to the old -- traditional plowing, and kind of traditional ways of weed control…hand weeding and plowing and those sort of things. And if we actually start seeing this product being lost again, you know, like Roundup, I think we're going to have to go back that direction.	p14: …first of all I don’t have any tillage equipment and I think it stirs up the seeds. And it just busts up the soil profile. It just changes the soil structure. It undoes everything I ever did over the last 20 something years, so tillage is just plain not an option.
24. Relying on auxin herbicides (2,4-D and dicamba)	p9: And I guess my next one looking at this is really going to be relying on you know auxin herbicides, either 2,4-D and Dicamba. You know that is probably what the guys might call the newest tool. You might need new, more tools, but this is the newest. It’s working very great, it's pretty much two shot kill. You know you're getting pretty much a guaranteed clean field… it’s in the forefront of how we are managing it now.	p21: …relying on auxin herbicides, using 2,4-Ds and Dicambas. I don't -- we try not to rely on them now, and I know that we'll be in the same situation with resistance if we continue to rely only on those, on that herbicide or that technology.