INCREASING THE RESILIENCE OF ORGANIC VEGETABLE SYSTEMS THROUGH AGROECOLOGICAL WEED MANAGEMENT.

by

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DEDICATION

I would like to dedicate this dissertation to my parents, Matt and Kelli Kubinski, for their sacrifice and determination to build me a life full of love, support, and opportunity. This dissertation is as much a testament to your hard work as it is to mine.

And to my husband, Tyler Kubinski. No matter how many things I learn and discover, you remain my greatest source of wonder. I'm so grateful to walk through life with you.

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ABSTRACT

Despite many efforts, weeds remain a major limitation to crop production, causing substantial yield losses and increasing management costs. Conventional management has focused on eliminating weeds through strong selection pressures, like herbicides and tillage. However, overreliance on these approaches led to herbicide resistance, soil erosion, and environmental concerns; highlighting the need for sustainable strategies. Ecological weed management (EWM) offers an alternative approach by shifting the focus from weed eradication to managing populations through ecological processes. However, key knowledge gaps remain for the application of EWM, including limited understanding of weed communities in organic vegetable systems, insufficient consideration of the impact of management decisions on crop yield and quality, uncertainty in how climate change may alter weed management strategies, and a lack of educational approaches that effectively teach EWM.

To address these gaps, this dissertation integrates field experiments, controlled-environment studies, on-farm surveys, and educational research. Field experiments quantified the critical period of weed control (CPWC) in organically grown carrots, incorporating both yield and quality, and evaluating opportunities for value-added use of imperfect produce. Growth chamber experiments assessed how elevated carbon dioxide (CO_2) influenced crop and weed growth, altering the length of the CPWC. On-farm surveys characterized weed community composition and functional traits across farms, crops, and years. Finally, an experiential learning exercise was developed to improve student understanding of EWM concepts and scientific writing.

Four main results emerged from this dissertation. First, the CPWC differed depending on whether yield or quality was prioritized, indicating that weed management based solely on yield may result in unexpected negative results. Second, elevated CO_2 altered plant growth and shifted CPWC timing, suggesting that climate change may modify management recommendations. Third, farm identity and year were the dominant factors determining functional diversity, indicating that farm-level management acts as a dominant filter shaping weed communities. Finally, the teaching exercise improved students' understanding of ecological underpinning of weed management and their scientific writing skills.

Overall, this research demonstrates how integrating ecological principles into weed management can improve decision-making, enhance resilience in organic vegetable systems, and better prepare future scientists and land managers to address emerging agricultural challenges.

CHAPTER 1

DISSERTATION OVERVIEW: BACKGROUND, RESEARCH GAPS, AND GOALS

Introduction to Ecological Weed Management

The Weed Science Paradigm Shift

Agriculture is facing increasing pressure to produce enough food to feed the exponentially growing human population, estimated to reach up to 12.6 billion people by 2100 (KC and Lutz 2017). Beyond this already immense pressure, more food must be produced with less available land while simultaneously facing the consequences of anthropogenic climate change, including more frequent and extreme weather events (Godfray et al. 2010). To ensure that agriculture can sustainably feed the growing global population, developing resilient agricultural systems is essential. One option to meet future food demand is to expand land used for food production; however, this would threaten the long-term capacity of ecosystems to provide goods and services (Foley at al. 2005). Alternatively, increasing agricultural productivity another important pathway to meeting future food demand. In this context, improving weed management is a key opportunity to reduce yield losses and improve efficiency (Tilman et al. 2002).

Globally, weeds decrease yields by up to 34% (Oerke 2006, Pimental et al. 2001). In response to their potential for substantial impact, weed science has historically been driven by a goal of eliminating as many weeds as possible from crop fields. This approach was empowered by the introduction of synthetic herbicides in the 1940s, which revolutionized weed control and

enabled growers to aim at achieving weed-free fields through chemical inputs (Shaner 2014). Reliance on herbicides for weed management was further reinforced by the introduction of herbicide resistant crops in the 1990s, such as “Roundup Ready” crops, which allowed non-selective herbicides to be applied directly to crops without damage (Shaner 2014). As a result, glyphosate use alone increased 15-fold following the adoption of herbicide-resistant cropping systems (Benbrook 2016).

However, this overreliance on herbicide use has imposed strong selection pressure on weed populations, leading to widespread development of herbicide resistance (Gaines et al. 2020). Currently, 273 weed species worldwide have developed resistance across 21 of 31 known herbicide modes of action (Heap 2026). The prevalence of resistant populations has increased reliance on additional or alternative herbicides, trapping land managers on the “pesticide treadmill” that reinforces dependence on external inputs and resulting increasing costs (Metcalf 1980). At the same time, growing concerns regarding human and environmental health impacts have led to increased regulation and opposition to herbicide use. Together, these combined factors indicate a transition toward a “post herbicide era” in weed science (Marshal 2019).

Beyond the limits of chemical inputs, modern weed management has been shaped by agricultural mechanization and industrialization, which have favored simplified cropping systems and standardized management practices designed for efficiency at scale (Altieri 1989; Gliessman 2004). These constraints limit the feasibility of diversified systems, such as polycultures, despite their well-documented benefits for weed suppression and system resilience (Fréville 2022; Sharma et al. 2021). In addition, industrial supply chains and market demands for uniform crop appearance, quality, and consistency favor the use of standardized varieties over

those adapted to local environmental conditions (Khoury et al. 2022; Altieri 2017), further reinforcing simplified cropping systems and exacerbating weed management challenges.

Collectively, these challenges highlight the limitations of a weed management paradigm focused on eradication. Despite decades of advancements in chemical control, weeds persist as a major constraint to agricultural productivity, suggesting that complete elimination is both unrealistic and unsustainable. To effectively manage weeds and build resilient agroecosystems, it is necessary to reconsider how weeds are described. Rather than the classic consideration of a weed as plants "out of place", weeds should be more accurately defined as "A plant, or population of plants, in a specific time and place, causing significant harm, either immediately or in the longer term, based on a holistic analysis of both their positive and negative attributes" (Merfield 2022).

Despite weeds being traditionally viewed only as competitors with crops, there is increasing evidence that they provide important benefits within socio-ecological systems. For example, weeds can improve soil health by improving soil structure (Arai et al. 2014), reducing erosion and runoff (Moreau et al 2020), and associating with beneficial soil microbes (Feldman and Boyle 1999; Sarathambal et al. 2014*;* Brito et al. 2013). Weedy species also provide critical resources for beneficial insects and wildlife (Balfour and Ratnieks 2022; Barbercheck and Wallace 2021; Marshall et al. 2003), including natural enemies of crop pests, and therefore, contribute to biological control (Landis et al. 2017). Beyond the ecological benefits, many weed species are edible and can contribute to food security (Ebel and Menalled 2024).

Ecological Weed Management

Recognizing weeds as important parts of the associated biodiversity requires a shift in how weeds are managed. Ecological weed management provides a framework for this change by emphasizing the application of ecological principles to regulate weed populations and communities (Liebman et al. 2001). Therefore, this approach moves away from weed eradication toward systems-based management (Harker and O'Donovan 2013; MacLaren et al. 2020).

There are four key principles that guide ecological weed management, all aimed at increasing the resistance of agroecosystems to weed species that threaten crop productivity and system function (MacLaren et al. 2020). First, increasing diversity in cropping systems, management practices, and weed communities is critical, as simplified systems tend to favor dominant, highly competitive species that contribute to yield loss (Adeux et al. 2019; Storkey and Neve 2018; Smith and Gross 2007; Weisberger et al. 2019). Greater spatiotemporal diversity in resource availability and disturbance regimes can reduce weed competitiveness by limiting consistent selection for dominant species (Smith et al. 2010). Second, reducing resource availability to weed populations through practices such as using competitive cultivars (Andrew et al. 2015) or considering the impact of fertility amendments on weed growth and competition is also important (Little et al. 2021). Third, consistent with the principles of integrated weed management (Swanton and Weise 1991), rather than relying on single, intensive control tactic, ecological weed management promotes the use of multiple, complementary strategies, often described as "many little hammers," to diversify selection pressures on weed populations (Clements et al. 2005). Finally, ecological weed management emphasizes recognizing and managing for the ecological benefits that weeds provide (Jordan and Vatovec 2004). Collectively, these principles reflect a shift from reactive weed control toward proactive, systems-based weed

management. Rather than responding to weed infestations after they occur, ecological weed management focuses on designing agroecosystems that regulate weed populations through ecological processes.

Organic Agriculture

For organic agriculture, the absence of synthetic herbicides makes the shift to ecological weed management especially relevant. Weeds have been identified as the biggest challenges in organic systems (Penfold et al. 1995; Stonehouse 1996). To mitigate yield losses from weeds, organic farmers rely heavily on mechanical and hand cultivation (Gallandt 2014). However, cultivation can contribute to soil degradation, including erosion, nutrient leaching, and loss of organic matter (Balesdent 2000) Hand cultivation often requires substantial labor inputs, increasing production costs in organic systems (Crowder and Reganold 2015). Additionally, these approaches often are less effective than chemical control, resulting in higher weed abundance in organic systems (Gallandt 2014).

One of the most challenging systems for weed management is organic vegetable production. Many high valuable vegetable crops are inherently weakly competitors (Van Heemst 1985). and require longer periods of weed management to maintain acceptable yields and quality (Knezevic et al. 2002; Ramesh et al. 2022), making them susceptible to yield loss from weed competition. Additionally, these systems are often highly diversified, requiring the simultaneous management of multiple crops with differing growth habits, planting schedules, and management requirements. As a result, growers must balance complex and often competing management demands, further complicating effective weed management.

Ecology and Weed Management

Ecological theory provides a foundation for understanding the mechanisms guiding the design of resilient weed management strategies. Several ecological theories are particularly relevant to weed management in organic vegetable systems, including community assembly, functional traits, and competition.

Community Assembly

A community, defined as an assemblage of species occurring at a given time and place (Begon et al. 1999), is shaped by the ecological processes that determine its composition and diversity. Keddy (1992) conceptualized community assembly as a series of filters that select species suited to certain conditions while excluding others, resulting in local communities composed of species able to persist under those conditions. The concept of community assembly underpins ecological weed management, as it describes how species from a regional pool are structured into local communities through the interaction of dispersal processes, environmental and biological factors, and the specific management tactics applied at the farm level (Booth and Swanton 2002; Diamond 1975; Weiher and Keddy 1999).

Assembly filters that structure community composition are typically categorized into three main types: dispersal, abiotic, and biotic filters (Belyea and Lancaster 1999). Dispersal filters determine whether propagules can reach a site at a given time and are influenced by landscape connectivity, dispersal mechanisms and transport via wind, water, animals, and humans, as well as stochastic biogeographical events (Lowe and McPeek 2014). Abiotic filters include climatic conditions, soil properties, resource availability, and disturbance regimes that determine whether species can persist under local environmental conditions. Biotic filters arise

from interactions among organisms, including competition, facilitation, herbivory, and pathogens determining which further regulate which species persist after establishment (Lortie et al. 2004).

Although community assembly is often described as a deterministic process driven by dispersal, abiotic, and biotic filters, stochastic processes must also be acknowledged. Dispersal limitation, random colonization events, and historical contexts can influence which species arrive at a site and when, contributing to variation in weed communities even under similar management conditions (Lowe and McPeek 2014). Neutral theory (Hubbell 2011), proposed as a null hypothesis to community assembly, provides a framework for understanding stochastic influences, suggesting that community composition is strongly influenced by processes like ecological drift and random establishment, rather than solely from differences in species traits or competitive ability. Despite the importance of stochasticity, evidence suggests that environmental filtering often exerts a stronger and more consistent influence on community composition than random processes alone (Gilbert and Lechowicz 2004; Cornwell et al. 2006).

Unlike natural systems, where filters are largely determined by environmental gradients, agroecosystems are unique in that management practices function as strong environmental and biological filters that influence weed community assembly (Booth and Swanton 2002). As a result, management decisions play a large role in determining which species are favored or excluded from the weed community. For example, crop planting time determines both the timing of disturbance and resource availability; therefore, influencing which weed species can establish. In a study of 561 arable fields, later planting dates were associated with shifts in weed phenology and structure, demonstrating how crop timing can act as a filter on community composition (Gunton et al. 2011). Nutrient management decisions also shift weed communities (Little et al.

2021), with long term experiments showing distinct differences in weed composition with varying nutrient inputs (Moss et al. 2004; Cordeau et al. 2021).

Weed control strategies themselves also act as filters. For example, tillage alters soil structure and redistributes seeds within the soil profile; therefore, influencing which weed species can emerge. Reduced tillage systems have been shown to favor certain life forms like perennial species and dispersal strategies, like small seeded species, while the timing of tillage operations further modifies which species are able to establish (Armengot et al. 2016; Derrouch et al. 2022; Zanin et al. 1997). Herbicides and simplified crop rotations also impose a strong filter on weed community composition favoring species tolerant of chemical control, adapted to these conditions (Storkey et al. 2010; Fried et al. 2012). As a result, these systems develop homogenized weed communities dominated by a small number of competitive species which are difficult to manage and more likely to cause yield losses (Adeux et al. 2019; Storkey and Neve 2018). On the other hand, alternative management approaches such as grazing or mechanical disturbance can lead to different community compositions (Ryan et al. 2010; Barroso et al. 2015). Cover crops also filter weed species community composition via both abiotic factors like by modifying light availability or via biotic factors like competition and facilitation (Adeux et al. 2023; Menalled et al. 2022; Smith et al. 2015).

MacLaren et al. (2020) explicitly connects community assembly to ecological weed management by equating the strength of filters with the selection pressures imposed by management practices. This aligns with the concept of “many little hammers” (Liebman and Gallandt 1997), where multiple management strategies are used to regulate weed populations rather than relying on a single, intensive control tactic. By diversifying management practices,

ecological weed management replaces strong, uniform filters with a range of weaker, interacting filters that reduce the likelihood of any single species dominating the community. Such approaches can create more heterogeneous conditions that limit the buildup of highly competitive weed communities, also known as neutral weed communities (Esposito et al. 2023), while encouraging species that provide ecosystem services (Navas 2012).

Functional Traits and Diversity

While community assembly explains how species are filtered into weed communities, the mechanisms underlying this process act on traits, rather than species. Specifically, community assembly works on functional traits which are measurable morphological, physiological, or phenological characteristics that influence a plant's fitness, including their ability to survive, reproduce, and interact with their environment (Lavorel and Garnier 2002). Therefore, community assembly can be understood as a process that selects specific trait combinations, with species persisting at a given time and place only if they possess the traits necessary to pass through dispersal, abiotic, and biotic filters. Garnier and Navas (2012) further distinguish functional traits into (1) response traits, which determine how species respond to environmental conditions and management, and (2) effect traits, which determine their influence on ecosystem processes, providing a mechanistic framework linking community assembly to ecosystem function.

Specific traits are associated with distinct plant ecological strategies. Commonly studied traits include specific leaf area, which reflects resource acquisition strategies; plant height, which influences competition for light; and seed mass, which affects dispersal and establishment (Westoby et al. 2002; Garnier and Navas 2012). Phenological traits are also highly influential in

agroecosystems, as they determine whether species are able to avoid or exploit disturbances such as planting, cultivation, or harvest (Gaba et al. 2017). The distribution and variability of these traits within a community is described as functional diversity (Petchey and Gaston 2006), a concept that provides insights into the structure and function of weed communities. For example, communities with low functional diversity are often characterized by high niche overlap and strong competition, whereas communities with greater trait diversity may exhibit niche complementarity, allowing species to utilize resources more efficiently and reduce competitive pressure (Petchey and Gaston 2006; Garnier and Navas 2012). In weed communities, greater functional diversity can lead to reduced crop yield losses, as it limits the dominance of highly competitive species (Adeux et al. 2019; Smith et al. 2010; Storkey and Neve 2018). Therefore, understanding functional traits, how management practices filter specific traits, and how those traits influence ecological outcomes, is essential for developing ecological weed management strategies that move beyond species-level weed management.

Competition

Building on the concepts of community assembly and functional traits, interactions among plants ultimately determine the impacts of weeds in agroecosystems. Competition occurs when plants share the same space and time and compete for limiting resources such as light, water, and nutrients, resulting in the suppression of neighboring plants through disproportionate resource capture (Zimdahl 2004).

Competition can be understood through niche theory, where a niche is defined as the environmental conditions and resources necessary for a species to persist, grow, and reproduce (Grinnell 1917; Hutchinson 1959). The intensity of competition between crops and weeds is

closely related to the degree to which their niches overlap (Zimdahl 2004). Weed-crop interference is greatest when weeds occupy similar niches to the crop, particularly in terms of resource use and phenology (MacArthur and Levins 1967; Smith et al. 2010). Conversely, niche differentiation allows species to coexist by utilizing resources differently in space or time, therefore reducing direct competition (Gause 1934; Hutchinson 1959; MacArthur and Levins 1967; Smith et al. 2010). Resource partitioning through differences in rooting depth, nutrient uptake strategies, or growth timing acts as a stabilizing mechanism by increasing intraspecific competition relative to interspecific competition, thereby promoting coexistence of weeds and crops with reduced negative impacts on crops (Esposito et al. 2023; Smith et al. 2010). Competitive interactions differ depending on how resources are acquired by plants. Belowground competition for water and nutrients is typically size symmetric, where plants acquire resources in proportion to their size (Casper and Jackson 1997; Cahill and Casper 2000). In contrast, aboveground competition is often size asymmetric, where larger individuals capture a disproportionately greater share of resources and suppress smaller neighbors (Weiner 1990; Weiner and Damgaard 2006). This asymmetry is particularly important in agroecosystems, where early differences in plant size can lead to strong competitive hierarchies that influence a crop's capacity for resource capture and growth.

Crops that establish quickly and achieve early size advantages, through factors such as emergence timing, seed size, or management practices that promote rapid growth, can gain a competitive advantage (Mohler 2001; Weiner 2001). Conversely, when weeds establish early or exhibit rapid growth, they may outcompete crops and reduce crop performance (Mohler 2001; Swanton et al. 2015). This is the ecological basis for the concept of the critical period of weed

control (CPWC), defined as the window when weed management is necessary to prevent unacceptable impact on crops (Nieto et al. 1968; Knezevic et al. 2002). Specifically, the CPWC helps us to identify when a crop is most vulnerable to competition.

In ecological weed management, competition is a key ecological process that can be manipulated to regulate weed populations and reduce their impact on crop performance. Specifically, ecological weed management seeks to shift competitive dynamics in favor of the crop while limiting the dominance of highly competitive weed species. Additionally, ecological weed management recognizes that competition within the weed community itself can contribute to weed population regulation (MacLaren et al. 2020). In more diverse systems, weed-weed interactions can limit the growth and dominance of aggressive species, reducing overall competitive pressure on the crop (Adeux et al. 2019; Storkey and Neve 2018). These dynamics are further shaped by niche differentiation and resource partitioning, which reduce direct overlap between crops and weeds, and allow for coexistence through complementary resource use (Smith et al. 2010). By managing competition rather than attempting to eliminate it, ecological weed management shifts the focus from eradication to the regulation of weed communities.

Research Goals, Knowledge Gaps, and Objectives

Despite the strong theoretical foundation used for ecological weed management, important gaps remain in the application of these concepts to organic vegetable systems. There is limited information on weed community composition in vegetable systems and little to no published documentation of weed communities on organic vegetable farms in Montana. This limits the development of regionally relevant ecologically based weed management recommendations. Additionally, while the critical period of weed control has been used to reduce

crop-weed competition, most studies focus on crop yield impacts rather than crop quality. Yet, in vegetable systems, quality often determines marketability and economic return, representing a critical gap in applied weed management research. Furthermore, climate change introduces additional uncertainty into ecological weed management recommendations. Elevated atmospheric CO_2 can alter plant growth, biomass allocation, and competitive dynamics, yet to my knowledge no study has evaluated how these changes may affect key management recommendations like the critical period of weed control. Finally, despite growing interest in ecological weed management, there remains a lack of educational materials that explicitly teach these concepts through systems level and experiential approaches. This limits the ability to effectively train future land managers and weed scientists to apply ecological principles in practice. To address these gaps, this dissertation integrates ecological theory with applied research and education to improve weed management in organic vegetable systems. Across chapters, this research examines weed dynamics from multiple ecological perspectives, including community assembly, competition, and experiential learning.

Chapter 2, *Managing Labor and Losses on Diversified Organic Vegetable Farms: The Critical Period of Weed Control (CPWC) to Optimize Yields and Value-Added Products of Carrots*, evaluates the critical period of weed control in organically grown carrots to determine when management is necessary to minimize yield losses and optimize crop quality. Grounded in competition theory, specifically asymmetric competition, this chapter addresses a key limitation of CPWC research by incorporating assessment of crop quality and useability for value-added products. Specifically, it asks: (1) What is the CPWC for organically grown carrots that enables growers to minimize yield loss due to weed competition? (2) Can the identified CPWC also be

used to optimize carrot quality? and (3) Are imperfect carrots suitable for value-added processing, including whether sugar content differs by quality and whether these carrots can be utilized by local food processors?

Chapter 3, *Does Climate Change Alter Weed Management Recommendations? Evaluating the Impact of Elevated CO_2 on Plant Growth and the Critical Period of Weed Control*, examines how elevated CO_2 concentrations influence plant growth and the critical period of weed control. Applying theories of competition and resource partitioning, this chapter evaluates whether climate driven changes in crop-weed interactions may alter future weed management recommendations. Specifically, it addresses the following questions: (1) How does elevated CO_2 affect plant growth, relative growth rate, and biomass allocation of model crop and weed species? and (2) Do these changes alter the length or timing of the CPWC?

Chapter 4, *Assessing Weed Communities on Organic Vegetable Farms Using Species and Trait Based Analyses*, characterizes weed community composition on organic vegetable farms in Montana and evaluates the effects of region, farm, and crop type on weed communities from both species and trait-based perspectives. Using community assembly theory and functional diversity, this chapter addresses the lack of regional data on weed communities in organic vegetable systems. It specifically asks: (1) How do region, farm, and crop type influence weed community composition by species? and (2) How do these factors influence weed community composition based on functional traits?

Chapter 5, *Teaching Ecological Weed Management: A Laboratory Exercise on Weed Community Assembly*, develops and evaluates a laboratory exercise designed to teach ecological weed management through community assembly and experiential learning. This chapter

addresses a critical gap in weed science education by providing a system-based approach to teaching ecological weed management concepts. It asks: (1) How was the laboratory exercise designed and implemented? (2) How did simulated cropping systems influence weed community composition? and (3) How did the exercise affect student understanding of ecological weed management, systems level thinking, and scientific writing?

Together, these chapters advance ecological weed management by integrating ecological theory with applied research and education to better understand and manage weed communities in organic vegetable systems. By linking community assembly, functional traits, competition, and management, this work contributes to the development of more resilient, ecological weed management strategies.

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CHAPTER TWO

CRITICAL WEED FREE PERIODS FOR YIELD AND QUALITY IN ORGANIC CARROTS AND VALUE-ADDED POTENTIAL OF IMPERFECT CARROTS

Contribution of Authors and Co-Authors

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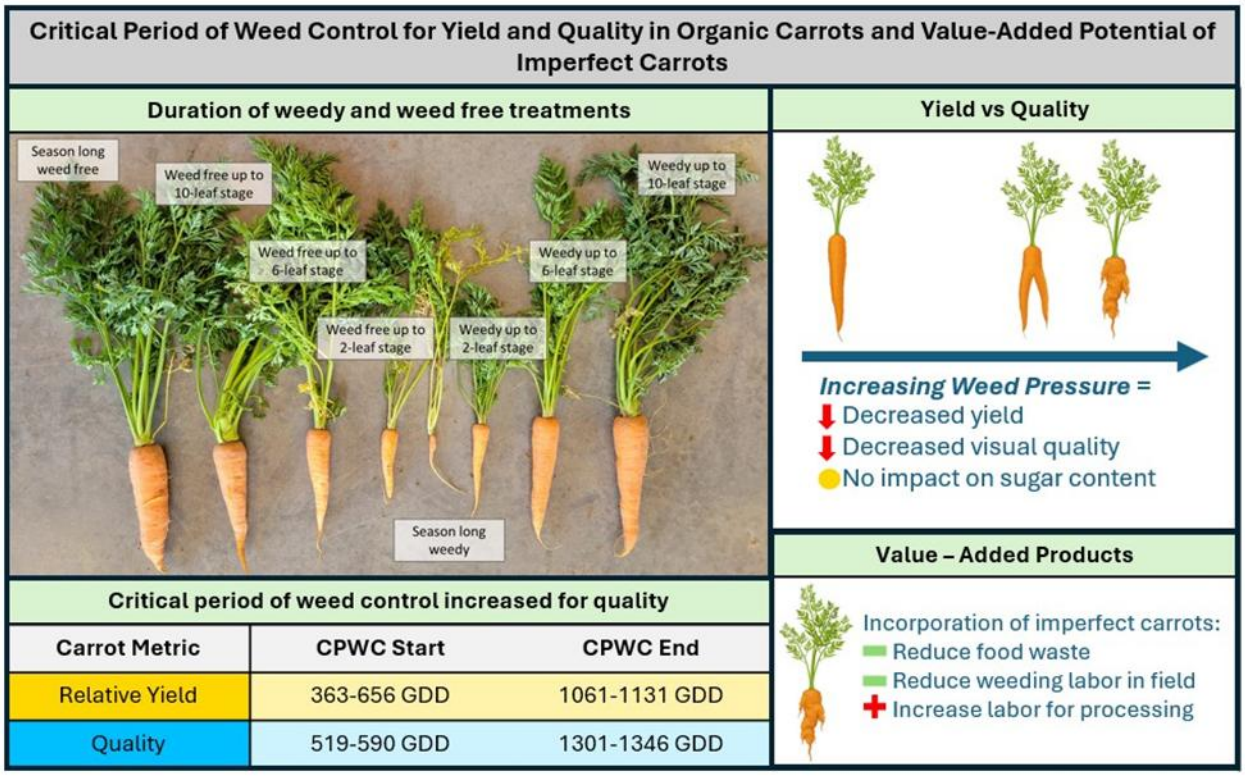
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Abstract

Weed competition is a major challenge for organic carrot production, often requiring intensive labor inputs to maintain acceptable yields and quality. This study evaluated the critical period of weed control (CPWC) in organically grown carrots to optimize time spent weeding for both carrot yield and quality, while also exploring opportunities to use cosmetically imperfect carrots for value-added products. Field trials were conducted in Bozeman, MT, USA, over two years across early and late planting dates, using a randomized complete block design with eight weeding treatments representing different durations of weedy or weed-free periods. The CPWC was evaluated using a 5% acceptable yield loss and measured in growing degree days (GDD) (base 3.33°C) to ensure transferability. The CPWC for relative yield started between 363-656 GDD and extended to 1061-1131 GDD. In contrast, the CPWC for quality started between 519-590 GDD and extended to 1301-1346 GDD, requiring an average of 233 additional weed-free GDD to maintain marketability compared to yield. This suggests that weed management based on yield thresholds may underestimate the time required to preserve crop quality, an essential trait in direct-to-consumer vegetable markets. Despite the impact of weed pressure on carrot yield and quality, sugar content remained unaffected, supporting incorporation of imperfect carrots into value-added products. Surveys with two food processors were conducted to assess the usability and market potential of carrots from different quality categories in value-added products. Results indicated that imperfect carrots could be used in value-added products depending on the form and processing method; however, increased labor requirements for cleaning and trimming lower-quality carrots limited their potential for incorporation. Findings

suggest that integrating CPWC based weed management with value-added strategies may help reduce food and labor losses and enhance the resilience of organic vegetable systems.



Graphical Abstract. Weed pressure reduces carrot yield and visual quality but not sugar content; the critical period of weed control is earlier for yield and extended for quality. Incorporating imperfect carrots into value-added products can reduce food waste and shift labor from field to processing.

Introduction

Achieving a sustainable agricultural and food system requires consideration of environmental, economic, and social dimensions across all stages, from food production to its commercialization and consumption. This is particularly relevant for small-scale organic vegetable farmers who, unlike commodity crop growers, sell fresh, unprocessed products directly to consumers, making visual quality a key factor in marketability. However, despite much research (Mohler et al., 2022), weeds remain one of the main threats to high-quality produce for

organic vegetable growers (Organic Farming Research Foundation, 2022). Weed competition not only reduces overall yields but also contributes to misshapen and unmarketable produce (McErlich and Boydston, 2014).

Without access to synthetic herbicides, organic growers rely on the integration of non-chemical weed management practices like cover cropping, mulching, enhancing crop competitiveness, and mechanical cultivation (Coleman et al., 2024). Yet, on smaller-scales and diversified farms, labor-intensive hand weeding remains a prevalent method of controlling weeds due to the limited mechanization in these systems (Coleman et al., 2024; Weil et al., 2017). As a result, labor costs on diversified vegetable farms account for upwards of 65 to 70% of farm production expenses (Weil et al., 2017). Rising farm wages and labor shortages make it essential to adopt strategies that optimize weed management labor while also sustaining crop yields and quality (Calvin et al., 2022).

An approach that growers can use to reduce labor demands is to concentrate weed management efforts during the critical period of weed control (CPWC) (Brown et al., 2019); i.e., the window of time a crop needs to be weeded to achieve acceptable yields (Nieto et al., 1968; Knezevic et al., 2002). The CPWC is determined by combining two different metrics, (1) the critical timing of weed removal, or how long the crop can coexist with weeds before there is a significant reduction in yield, and (2) the critical weed-free period, or the minimum amount of time the crop must remain weed free to maintain high yields (Knezevic et al., 2002). Despite its potential, reviews of CPWC studies indicate that nearly all studies on the CPWC have been conducted on conventionally grown commodity crops (Ramesh et al., 2021; Van Heemst, 1985) In the few vegetable crops where the CPWC has been determined, studies have predominantly

been conducted in conventional systems where herbicides and other synthetic inputs were used (Amador-Ramírez, 2002; Chaudhari et al., 2016; Fadlallah, 2019; Swanton et al., 2010; Qasem, 1995; Weaver, 1984). Thus, limiting their applicability to organic systems and leaving a knowledge gap for organic vegetable systems where reducing weeding labor costs is particularly important.

Utilizing the CPWC is especially advantageous for crops with poor competitive ability, which require high labor demands to mitigate weed pressure and maximize crop quality. A prime example is carrot (*Daucus carota*), one of the least competitive crops (Van Heemst, 1985). Carrots' lack of competitiveness can be attributed to the crop's direct seeding, slow emergence, and limited early season growth, delaying canopy closure (Colquhoun et al., 2017). Consequently, organically grown carrots require high labor inputs of hand weeding, with estimates ranging from 100 to 500 hours/ha^{-1} (Tei et al., 2002). In addition to decreasing overall yields, weed competition in carrots contributes to reduced crop quality, leading to lower marketable yields due to smaller and deformed roots that are forked, bent, or stunted, ultimately reducing marketability (Abdel-dayem et al., 2022; Dresbøll et al., 2008; Kaur et al., 2022).

In the United States, nearly 40% of produce is discarded before reaching consumers, often due to visual imperfections (Gunders, 2012). Consumers associate imperfect produce with inferior nutritional value, safety, and economic worth (Yuan et al., 2019), resulting in substantial quantities of produce being left unharvested or disposed of at the retail level (Porter et al., 2018). One strategy to utilize these imperfect vegetables is to incorporate produce with poor marketability into value-added products (Bhatt et al., 2017), i.e., produce that has undergone a change in its physical state or form to enhance its value (Agricultural Marketing Resource Center

n.d.). This allows producers to reduce food waste while simultaneously opening new revenue sources.

Given the high labor demands and poor competitive ability of carrots, improving weed management and finding alternative markets for imperfect produce is imperative. While the CPWC has been applied to optimize carrot yields (Fadlallah et al., 2019; Swanton et al., 2010), it has not been studied in organic vegetable systems. Furthermore, its relevance to crop quality, an essential consideration for vegetable producers marketing fresh produce, remains largely unexplored.

Yield loss and physical deformities caused by weed competition may not be proportional, raising questions about whether the CPWC is sufficient to protect both yield and quality. We therefore hypothesized that the CPWC defined by visual quality would differ from that defined by yield alone and expected that weed interference could reduce carrot quality even when biomass reductions were limited, thereby lengthening the weed-free period required to maintain marketability.

To address these hypotheses, we assessed the following research questions: (1) What is the CPWC for organically grown carrot that allows growers minimize yield losses due to weed competition? and (2) Can the identified CPWC also be used to optimize organic carrot quality? We further evaluated whether imperfect carrots were suitable for value-added product processing by addressing the following question: (3) Can imperfect carrots be used for value-added products by local food processors?

Materials and Methods

Experimental Design

This study was conducted in 2021 and 2022 at the Towne Harvest Garden, a certified organic research and teaching farm managed by Montana State University in Bozeman, MT, USA. Four total trials were carried out: 2021 early planting, 2021 late planting, 2022 early planting, and 2022 late planting. Trials were established at separate irrigated field locations each year to reflect typical organic crop rotations. A mustard (Brassica spp.) cover crop preceded carrots in 2021, and winter squash (Cucurbita spp.) in 2022.

Farm level weed surveys were conducted in carrot production areas at Towne Harvest from 2022-2024. Across years, dominant species included warm-season annuals such as Chenopodium album and Amaranthus retroflexus, primarily cool season annuals including Lamium amplexicaule and Malva neglecta, and perennial species including Cirsium arvense and Taraxacum officinale, with relative abundance varying across years. This assemblage represents a mix of early and mid-season emerging species typical of organic vegetable systems in the region.

During the growing season, the mean annual temperature was 19.9°C and 19.2°C in 2021 and 2022, respectively, and total precipitation was 72.1 mm and 90.7 mm in 2021 and 2022, respectively. The soil at the site is a loam with moderate organic matter content (2021 in 3.5%, 2022 in 3.1%). Soil tests were taken in late May (0-24 cm depth) in both 2021 and 2022. Nitrate-nitrogen concentrations averaged 9.9ppm in 2021 to 11.5 in 2022 in the 0-6 cm layer and 9.2 ppm in 2021 and 7.4 ppm in 2022 in the 6-24 cm layer. Olsen phosphorus levels ranged from

87ppm in 2021 and 96 ppm in 2022, and potassium averaged from 704 ppm in 2021 and 773 ppm in 2022.

In all trials, early-season weed management was conducted through multiple tillage passes ahead of planting. To prepare a fine seedbed for carrot seeding, fields were subsequently rototilled and then cultivated with a S-tine, following standard practices for the region. In both years, the cultivar 'Hercules F1' was selected for its prior success under local conditions, adaptability, cold hardiness, and storage capacity, which make it well suited for fall harvest. Seed was sourced from Johnny's Selected Seeds (Winslow, ME, USA) and complied with organic production standards. Pelleted carrot seeds were sown using a Jang tractor-mounted seeder to ensure uniform spacing and planting depth. Carrots were planted 5 centimeters apart and approximately 2.5 centimeters deep, in four-row beds with 30 centimeters spacing between rows. Early-season plantings occurred on 3 June (2021) and 23 June (2022), while late-season plantings took place on 28 June (2021) and 14 July (2022). Early and late plantings were established in adjacent beds within the same field.

Each year, the experimental design consisted of a randomized complete block design with four replications per treatment. Each experimental plot was 2.5m x 4 rows with eight randomly assigned weeding treatments imposed to create defined duration of interference: 1) weedy up to the 2-leaf stage, 2) weedy up to the 6-leaf stage, 3) weedy up to the 10-leaf stage, 4) weed free up to the 2-leaf stage, 5) weed free up to the 6-leaf stage, 6) weed free up to the 10-leaf stage, 7) season-long weedy, and 8) season-long weed free. Treatments were maintained by hand weeding once to twice a week, depending on weed pressure.

In 2021, harvests occurred on 3 September (early planting) and 24 September (late planting); in 2022, carrots were harvested on 5 October (early) and 21 October(late). From each plot, 20 carrots were randomly selected for data collection. Root biomass (fresh weight) was measured individually for each of the 20 selected carrots per treatment after removing aboveground foliage. Roots were gently cleaned of soil and weighed immediately after harvest using a digital scale (±0.1 g precision).

Additionally, all 20 carrots from each plot were evaluated for visual quality using a 5-point ordinal scale, where 1 indicated the lowest quality and marketability and 5 represented the highest. Quality ratings were based on overall marketability, including root shape uniformity, incidence of forking or splitting, surface defects, and size relative to fresh-market standards. Carrots receiving a score of 1 were severely misshapen; forked, split, or otherwise damaged, and were deemed unmarketable for direct-to-consumer sales. In contrast, carrots rated as 5 had uniform, cylindrical shapes, were undamaged, and of sufficient size for sale. Scores of 2-4 represented intermediate levels of cosmetic deformity, with increasing marketability from 2 (substantially misshapen but partially usable) to 4 (minor imperfections but marketable). Visual quality assessments were conducted by multiple trained evaluators. Prior to scoring and to minimize scoring variability among evaluators, we conducted a calibration session where representative carrots from each quality category were jointly reviewed to standardize the scoring criteria. Of the 20 carrots from each treatment, a randomly selected subset of 5 was used to measure total soluble solids (Brix°), using a digital refractometer (Model HI96801, Hanna Instruments, Woonsocket, RI, USA). Total soluble solids are predominately composed of soluble

sugars and are used as a practical indicator of perceived sweetness, and therefore taste, in carrots and other horticultural crops (Carvalho et al., 2020; Magwaza and Opara, 2015).

In addition, we worked with two local food processors which make value-added carrot-based products. Specifically, one food processor evaluated the feasibility of incorporating carrots from each quality category into their curried carrot pickles, while the second assessed their use for spicy fermented carrot chips. Each processor received approximately 2 kg of carrots from each quality category (1-5). Based on the samples provided, processors completed a questionnaire for each quality category, indicating whether the carrots could be used, labor requirements for each quality category of carrots, and how much they would be willing to pay farmers for carrots of varying quality per pound. Despite the small sample size, this collaboration provided preliminary insight into the potential for processing weed-impacted carrots and their marketability within value-added supply chains.

Statistical Analysis

To assess treatment and trial effects, a factorial ANOVA was performed for three response variables: carrot root biomass, average marketability/quality scores, and sugar content. Linear models of the form: response~Treatment+Trial were fitted, followed by Tukey's Honest Significant Difference (HSD) post-hoc tests for pairwise comparisons. Interaction terms (Treatment × Trial) were also tested to evaluate potential variability in treatment effects across trials. To further evaluate how response variables related to each other, Pearson correlation and linear regression analyses were conducted for individual trials for the root biomass vs. quality and quality vs. sugar associations. All models and boxplot visualizations were implemented in R (R Core Team, 2024) using the multcomp, ggplot2, and dplyr packages.

To generalize results and allow for comparison across years and trials, weeding treatments were correlated with accumulated growing degree days (GDD); i.e., the accumulated temperature from crop planting to treatment timing. The GDD was calculated using a base/minimum temperature of 3.33°C and an upper/maximum temperature of 30°C for carrots as recommended by Oregon State Extension (Andrews, 2011). Temperature data was collected from an on-site weather station. The critical period of weed control (CPWC) was estimated using yields or quality data and GDD following Knezevic and Datta (2015), using the following four-parameter log-logistic regression model:

$$Y = C + \frac{D - C}{1 + [B(logX - logE)]}$$

where *Y* represents the relative response of the variable of interest (i.e., relative yield or marketability/quality score, relative to the season-long weed-free control), *C* and *D* are the lower and upper asymptotes, *X* is time expressed as GDD, *E* is the GDD at the inflection point (50% response between *C* and *D*), and *B* is the slope at the inflection point. Separate models were fit for the weedy and weed-free treatments for each year and planting and for both response metrics (relative yield and quality). Average plot-level quality scores were treated as continuous response variables in dose-response modeling. Analyses were conducted in R (R Core Team, 2024) using the *drc* package (Ritz et al., 2015), with the l4 function applied to fit the log-logistic response curves.

Model fit was assessed using lack-of-fit tests (modelFit() function), which compared the residual sum of squares of the fitted model to that of an ANOVA model. A non-significant p-value ($p > 0.05$) indicated an adequate fit of the log-logistic model to the data. In addition, model assumptions were evaluated for each site-year analysis by inspecting residual versus fitted value

plots to assess homogeneity of variance and by examining normal Q-Q plots to assess residual normality. Across all models, residuals were approximately symmetrically distributed around zero with no consistent patterns of heteroscedasticity. Minor deviations in the distribution tails were observed in some years and trials but were not systemic. Based on these diagnostics, data transformations were not required. For all models, upper (*D*) and lower (*C*) limits were fixed using observed values from the experiment: *D* was set to the maximum observed yield/quality in the season-long weed-free treatment, and *C* to the minimum yield/quality observed in the season-long weedy treatment for the associated trial ensuring that CPWC estimates reflected the biologically observed yield/quality range.

Based on a 5% acceptable yield/quality loss threshold, the beginning of the CPWC was identified as the point in time at which relative yield or quality fell below 95% of the weed-free maximum, estimated from the weedy treatment model. Similarly, the end of the CPWC was identified as the point at which treatments did not maintain a yield or quality below 95% of the season long weed-free condition. In most cases, CPWC thresholds were estimated using the ED() function in the *drc* package in R, which calculates effective dose levels based on the fitted model and provides associated standard errors derived from the model's parameters. However, in 2022, model weed-free curves extended beyond the observed data range for relative yield, resulting in biologically implausible estimates of the CPWC endpoint (i.e., after harvest date). In these cases, we constrained estimation to the observed GDD range and identified the first point where the fitted curve reached 95% of the weed-free maximum. This approach does not offer standard error estimates, so confidence intervals for these endpoints were not reported. The use of constrained curve based thresholds parallel the methods used in earlier CPWC studies (Weaver 1984) but

uses fitted regression models rather than direct comparison of treatment means. To examine potential trade-offs between yield and quality, the overlap in GDD ranges between CPWC intervals defined by relative yield and quality was calculated. While the relationship between carrot quality and sugar content was assessed, no formal statistical analysis was conducted on the value-added processor survey responses due to the limited sample size (n = 2), and results should be considered cautiously rather than statistically conclusive.

Results

Root Biomass, Quality, and Sugar

Treatment × Trial interaction terms were not significant, indicating that the effects of weeding treatments on response variables were consistent across years and planting timings (Quality: $p = 0.88$; Root Biomass: $p = 0.96$; Sugar: $p = 0.26$). However, the main effect of trial was significant for all response variables ($p < 0.001$), indicating that overall response levels differed among years and planting timings. Weeding treatment affected root biomass (Figure 1) ($p < 0.001$, for all trials) and quality (Figure 2) ($p < 0.004$, for all trials). To contextualize results, Figure 3 presents representative carrots from both weedy-until and weed-free-until up to successive carrot leaf stages, highlighting smaller roots with longer weed interference. In contrast, sugar content showed a weak treatment effect in only the early planting trial of 2021 ($p = 0.012$) and no effect in the others ($p = 0.44$, for all trials).

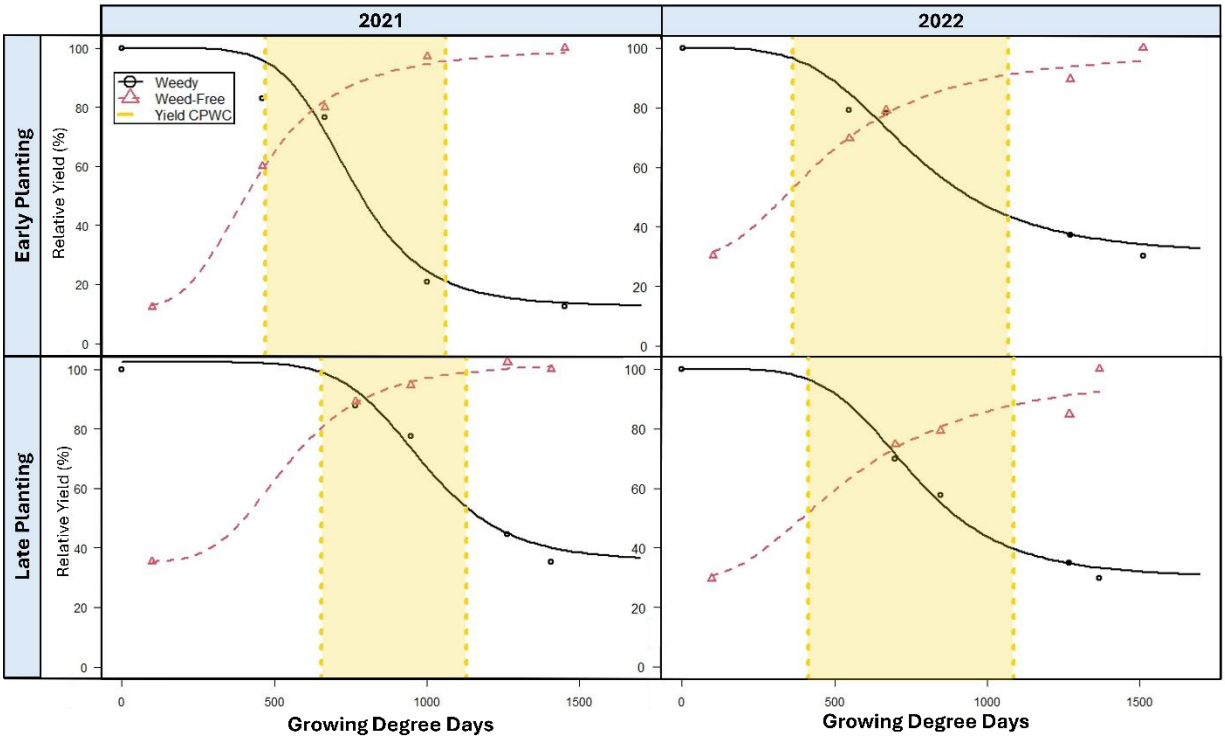


Figure 1: Relative carrot yield (%) in response to increasing weed interference duration (weedy, solid black line) and weed-free period (weed-free, dashed red line) across planting dates (early vs. late) and years (2021 and 2022). Points represent treatment-level means, and lines represent fitted four-parameter log-logistic models based on accumulated growing degree days (base temp 3.33°C) from carrot emergence. The shaded yellow region denotes the relative yield critical period of weed control (CPWC).

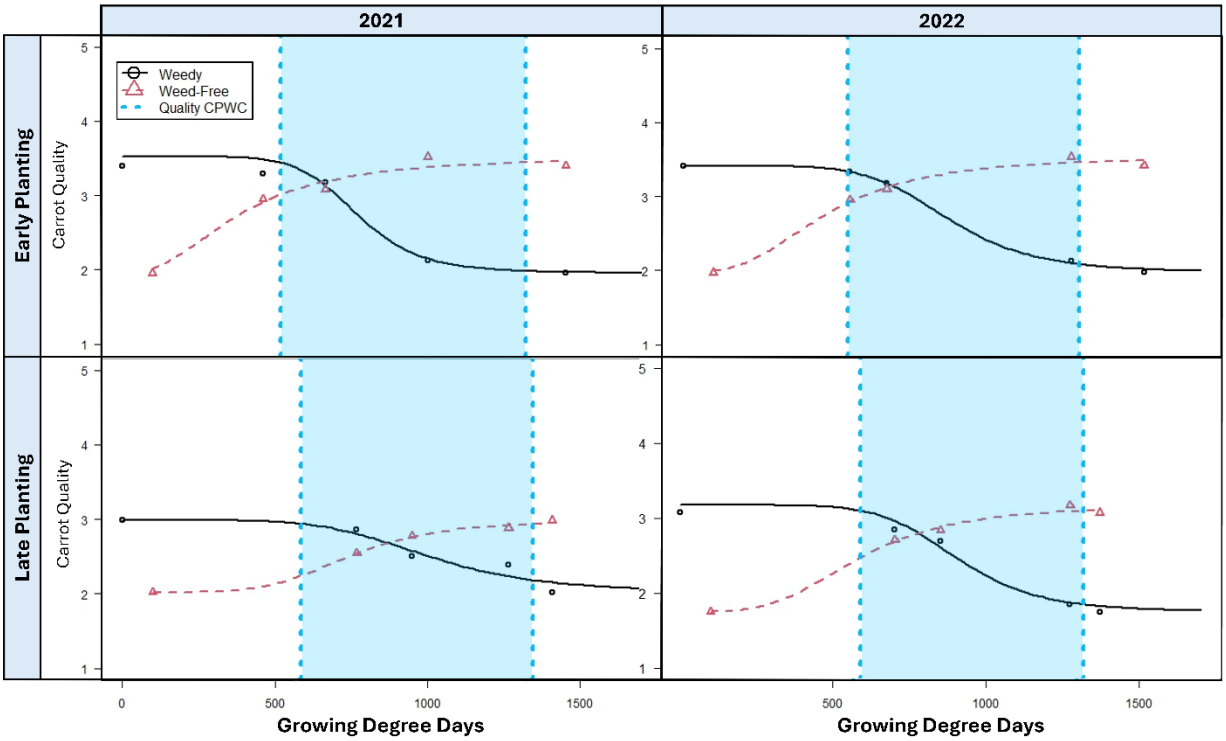


Figure 2: Carrot marketability/quality (qualitative scores 1-5) in response to increasing weed interference duration (weedy, solid black line) and weed-free period (weed-free, dashed red line) across planting dates (early vs. late) and years (2021 and 2022). Points represent treatment-level means, and lines represent fitted four-parameter log-logistic models based on accumulated growing degree days (base temp 3.33°C). from carrot emergence. The shaded blue region denotes the critical period of weed control (CPWC).



Figure 3: Representative carrots from weeding treatments demonstrating differences in root size due to weed competition.

Pairwise comparisons using Tukey's Honest Significant Difference test showed that season-long weedy treatments consistently produced the lowest root biomass and quality scores. For example, in the early planting trail in 2021, carrots from season-long weedy plots weighed 84.8 g ± 6.5 g less, or an 85.8% decrease in root yield, than those from season-long weed-free plots ($p < 0.001$) and scored 1.3 ± 0.2 points lower in quality ($p < 0.001$). Although the magnitude of response varied slightly across trials, the direction of treatment effects was consistent.

Correlation and regression analyses were conducted at the plot level within trials (n = 32 plots per trial). A positive association was observed between carrot root biomass and quality, with coefficients of determination ranging from $R^2 = 0.45$ to 0.61 (all $p < 0.001$), indicating that

higher-biomass carrots tended to receive higher marketability scores. However, these R^2 values indicate that a proportion of variation in quality remained unexplained. Linear regression showed that each 1.0 g increase in root biomass associated with a 0.01 increase in quality ($p < 0.001$, R2 = 0.35). In contrast, the association between quality and sugar content was weak overall (R^2 = 0.01, $p = 0.39$). Only the early planting trial of 2021 showed a moderate positive association (R^2 = 0.32, $p < 0.01$), with no associations in other years.

Critical Period of Weed Control

Model fit was adequate across all years and plantings for both response variables, with no evidence of lack of fit ($p > 0.05$). The CPWC for relative yield varied across years and planting timing, with start points ranging from 363.1 (± 62.0) GDD (± SE) (2022, early planting) to 656.1 (± 80.0) GDD (± SE) (2021, late planting) and end points ranging from 1060.7 (± 375.8) GDD (± SE) (2021, early planting) to 1130.6 (± 406.4) GDD (± SE) (2021, late planting) (Figure 1). The CPWC for quality did not vary as substantially as for relative yield. Still, results varied across years and planting timing, with start points ranging from 519.33 (± 110.6) GDD (± SE) (2021, early planting) to 590.1 (± 123.2) GDD (± SE) (2022, late planting) and end points ranging from 1301.2 (± 859.8) GDD (± SE) (2022, early planting) to 1345.7 (± 376.0) GDD (± SE) (2021, late planting) (Figure 2)Across years and planting timing, the total length of CPWC for relative yield was generally shorter than the one for quality, but the extent to which they differed varied between years (Figure 4). In 2021, the CPWC for relative yield was 208.3 GDD shorter than that for quality in the early planting and 284.7 GDD shorter in the late planting. In 2022, the difference was smaller, with the relative yield CPWC 52.4 GDD shorter in the early planting and 56.6 GDD shorter in the late planting, compared to the quality based CPWC. In both trials in

2022, and the earlier planting in 2021, the relative yield CPWC started earlier than the quality CPWC. In all trials, the quality CPWC ended later than the relative yield CPWC, requiring an average of 233.4 ± 20.0 GDDs to maintain acceptable quality levels.

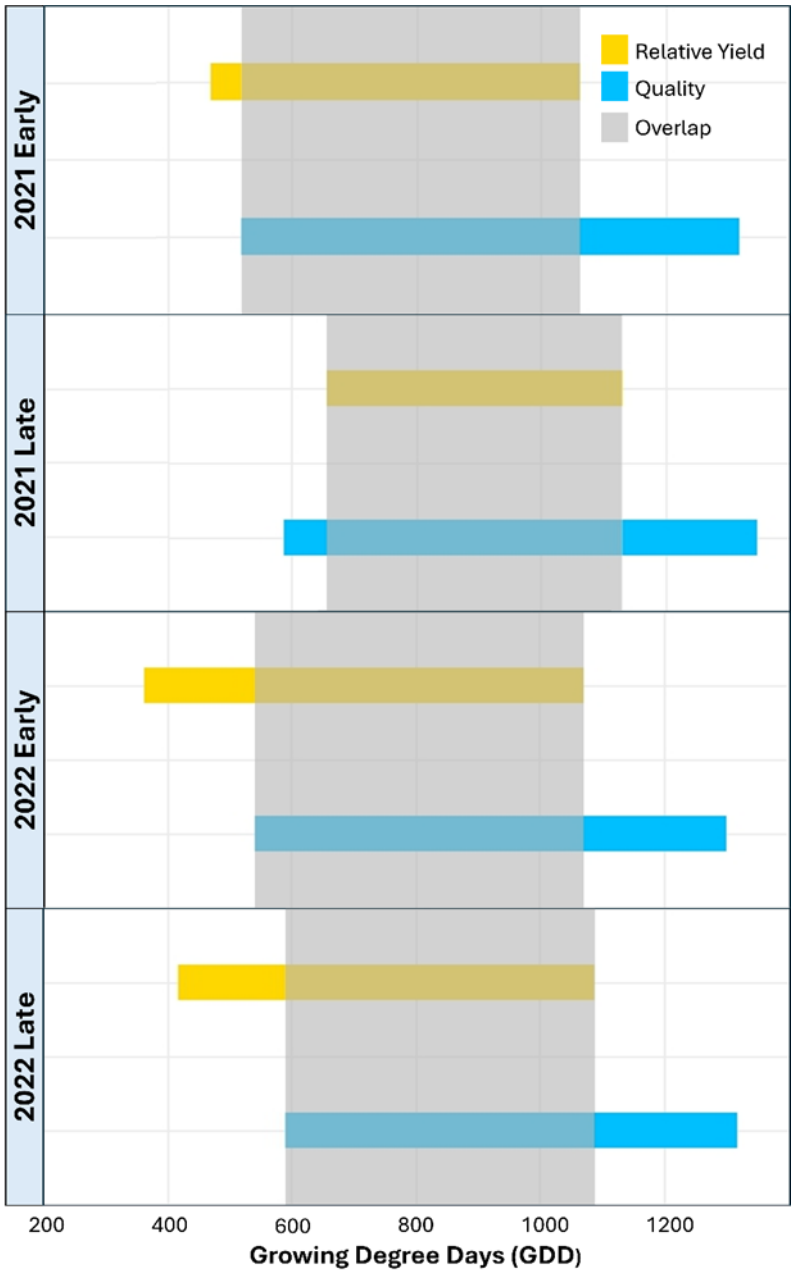


Figure 4: Comparison of the critical period of weed control (CPWC) based on relative yield (yellow) and crop quality (blue) for organic carrots across years and planting dates. Each horizontal bar represents the CPWC duration in growing degree days (base temp 3.33°C) from

crop emergence. The shaded gray regions indicate the overlap between yield- and quality-based CPWC estimates.

Value-Added Products

The spicy fermented carrot chips food processor indicated their willingness to use carrots from all five quality categories, though they expressed minor concerns about carrots with a quality score of 1 due to cleaning difficulty. Nevertheless, they considered even the lowest-rated carrots to be at least partially usable. In contrast, the curried carrot pickles company stated they would not use carrots from quality scores of 1, 2, and 3, but could incorporate 4 and 5 quality into their curried carrot pickles.

The price these two food processor companies were willing to pay for carrots increased with quality. The spicy fermented carrot chips food processing company was willing to pay 27% less per kg for the lowest quality carrots (Rating 1), and 13% less per kg for low quality carrots (Rating 2) compared to mid to highest quality carrots (Ratings 3, 4, 5). The curried carrot pickle food processing company was more selective, citing concerns over processing labor and visual appeal. They were not willing to use carrots from the lowest, low, and middle quality categories (Rating 1, 2, 3) but indicated willingness to purchase high and highest quality carrots (Ratings 4 and 5), with high-quality carrots valued at 31% less per kg than the highest quality category.

The reduced value of lower rated carrots was largely attributed to increased labor demands during processing i.e. cleaning, cutting, and preparing carrots for fermentation. The spicy fermented carrot chips company reported processing rates of ~0.7 kg/hour for the lowest-quality carrots (Ratings 1 and 2), increasing to ~0.9 kg/hour for higher quality carrots (Ratings 3, 4, 5). In contrast, the curried carrot pickle company related more variable processing time, with rates of ~0.5 kg/hour for Rating 3, ~0.6 kg/hour for Rating 4, and ~0.9 kg/hour for Rating 5.

Discussion

To our knowledge, this is the first study to jointly evaluate the CPWC in organically grown carrots and to assess the implications of CPWC for both crop yield and quality. Furthermore, we explored how imperfect carrots may be integrated into local value-added processing. Consistent effects of weeding treatment on carrot yields and quality across all trials underscores the influence weed competition has on organic carrot production. Our results agree with various studies that have demonstrated that both the yield and quality of carrots are vulnerable to weed crop competition (Coelho et al.,2009; Colquhoun et al., 2020). In all four trials, carrots grown in season long weed competition had reduced root biomass and lower marketability compared to those in weed free plots. In contrast, sugar content remained unaffected by weeding treatment, suggesting that weed pressure may have minimal impact on flavor related traits.

The CPWC for organic carrots was successfully estimated, with the yield based period beginning between 363.1 and 656.1 GDD (base 3.33°C) and ending between 1061.0 and 1131.0 GDD (base 3.33°C). While our findings show some consistency with previous work in conventional systems, they also highlight notable differences. Swanton et al. (2010) determined the minimum weed-free period required for carrots to prevent unacceptable yield loss (i.e. the end of the CPWC) to be 414.0 GDD to 930.0 GDD (base 5°C with a 5% acceptable yield loss). Our results suggest that organic carrot growers must maintain carrots weed free for longer to achieve a similar yield loss threshold as their conventional counterparts. The increased minimum amount of time organic carrots must remain weed free can be attributed to differences in management practices and mechanisms driving weed crop competition between conventional

and organic agroecosystems. For example, Swanton et al. (2010), used Linuron (3-(3,4-dichlorophenyl)-1-methoxy-1-methylurea) early in the season to control broadleaf weeds. Linuron is widely used in conventional carrot production due to its pre- and early post-emergence activity as well as its residual weed suppression (Bellinder et al., 1997). This early-season herbicide likely extended weed control during the early growth stages of the carrot crop. In contrast, our study relied on mechanical cultivation and hand weeding for early season weed management which typically provides less consistent and shorter-lived weed control compared to herbicides (Bàrberi, 2002; Riemens et al., 2007).

Differences in fertilizer application and nutrient dynamics between organic and conventional agroecosystems may have also influenced the length of the CPWC (Evans et al., 2003; Little et al., 2021; Tursun et al., 2015). Conventional systems typically apply synthetic fertilizers in concentrated, plant-available forms early in the season, promoting rapid crop growth, earlier crop canopy closure, and a flush of fast-growing weeds (Jørnsgård et al. 1996; Liebman and Davis 2000). In contrast, organic systems rely on mineralization of organic matter and organically approved fertilizers, which release nutrients gradually over time (Liebman and Davis, 2000). Thus, fertility management strategies may indirectly influence CPWC through their effects on early crop growth and weed competitive pressure.

Contrasting nutrient dynamics coupled with the absence of herbicide use contributes to more weeds typically observed in organic systems compared to conventional systems (Bengtsson et al., 2005; Edesi et al., 2012). Despite the greater abundance of weeds, organic systems have been found to be more resistant to yield losses from weed competition (Ryan et al., 2009). This resilience has been attributed to increased weed species diversity, more heterogeneous nutrient

availability, shifts in the functional composition of weed (Cordeau et al., 2021; Smith et al., 2010). Also, changes in the associated soil-microbial communities (Ishaq et al., 2017), in turn, modify plant growth and plant-plant interactions with relatively less crop-weed competition in organic cropping systems that in conventional systems (Johnson et al., 2016).

Despite the differences between conventional and organic systems, our results agree with Swanton et al. (2010) as carrots planted later in the growing season required a shorter weed-free period to maintain acceptable yields. Thus, delaying planting can enhance carrot emergence and early growth due to warmer soil temperatures, while also reducing the number of weeds that emerge between tillage and planting (Colquhoun et al., 2020).

Although we observed variability in CPWC duration between planting timings, the greatest differences occurred between years. Several factors could explain this pattern. Although all plots were irrigated, 2022 received more rainfall than 2021, which may have supported more flushes of weeds, prolonging weed emergence and interference (Swanton et al., 2010). Additionally, interannual differences in weed communities may have influenced competitive dynamics. Weed species composition, density, and biomass were not systematically quantified within experimental plots, precluding us to attribute variation in CPWC duration to specific weed community differences.

Differences in prior field management could have also influenced weed pressure and the length of the CPWC. The 2021 field had previously been planted with a mustard cover crop, known for its weed-suppressive properties (Björkman et al., 2015; Haramoto and Gallandt, 2005). In contrast, the 2022 field followed a winter squash cash crop that provided less residue-mediated suppression of weed emergence prior to carrot establishment. In agreement, previous

research demonstrated that high residue cover crops can delay the critical time for weed removal and, in some cases, shorten the overall critical period of weed control (CPWC) by suppressing early season weed emergence (Korres and Norsworthy, 2015; Price et al., 2018; Kumari et al., 2023a; Kumari et al., 2023b). Overall, our results reinforce the idea that the CPWC should be applied as an adaptive management guideline that accounts for site-specific factors, including prior management history, environmental conditions, and weed community composition (Ramesh et al., 2021).

Our results demonstrate that weed interference reduced not only total carrot yield but also increased the proportion of misshapen or undersized roots. This has vital implications for management decisions when visual quality is closely tied to price premiums (Hartmann et al., 2021; Grewal et al., 2018) as growers must consider tradeoffs with economic and labor demands required more weeding to preserve their desired crop marketability. However, it should be noted that carrot quality is influenced by multiple interacting factors beyond just weed competition, including cultivar characteristics, soil structure, environmental stress, pests, soilborne pathogens, and storage (Bender et al., 2021; Johansen et al., 2015; Paparella et al., 2024; Suojala, 2000).

We also explored the potential for value-added processing of carrots that do not meet quality standards for fresh market sales. Results show carrot sugar content, and thus perceived sweetness, remained unaffected regardless of their quality rating. This suggests that cosmetically imperfect carrots may be suitable for juicing, fermenting, or other processing uses. These findings align with Elimelech et al. (2024), who reported that consumers generally did not perceive notable taste differences between visually perfect and imperfect vegetables, and in some cases, rated the imperfect produce as better tasting than its higher visual quality counterpart.

However, while sugar content serves as a useful indicator of perceived sweetness, a more comprehensive assessment of flavor quality should include additional metrics such as concentrations of 6-methoxymellein (6-MM), soluble phenolics, and organic acids in relation to moisture content which has been found to be indicative of carrot taste (Talcott et al., 2001).

Interviews with two local processors suggested that imperfect carrots were acceptable for some value-added products, particularly those focused on flavor rather than form; however, given the limited sample size, these findings should be interpreted as preliminary and context specific. In our study, the processor that used curried carrot sticks that required longer, more uniform carrots compared to the chopped carrot chips was limited in their ability to incorporate misshapen produce. It is possible that other value-added products that use carrot juice or purée like hot sauces and smoothies may be able to more readily incorporate misshapen produce due to lack of limitations of produce size. Specifically, Barone et al. (2023) demonstrated that transforming misshapen items into value-added products that completely change the shape increases consumer acceptance by making the product a more “prototypical” example of its new category.

In addition to limited incorporation to fit product standards based on shape, food processing companies also reported that lower-quality carrots often required more labor to trim or clean, which reduced processing efficiency and increased costs. These findings suggest that while quality losses due to weed interference may be partially recouped through incorporation into value-added products, labor availability and processing constraints must be considered when designing value-added product recovery strategies.

Conclusion

This study demonstrated that the CPWC can serve as a practical decision tool for managing labor demands while maintaining both yield and quality in organic carrot production. Findings demonstrate that the CPWC for visual quality extends beyond that for yield, underscoring the importance of quality based thresholds for growers targeting direct-to-consumer markets. At the same time, results show that imperfect carrots maintain perceived sweetness levels and may be suitable for select value-added products, especially when the final product form masks initial appearance. By integrating CPWC recommendations with strategies to repurpose lower-quality produce, growers may reduce on-farm food loss, improve labor efficiency, and access new markets. Collectively, these findings establish CPWC as a systems based framework for aligning weed management, market goals, and food loss reduction, addressing key sustainability challenges in diversified organic vegetable systems.

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CHAPTER THREE

DOES CLIMATE CHANGE ALTER WEED MANAGEMENT RECOMMENDATIONS? EVALUATING THE IMPACT OF ELEVATED CO_2 ON PLANT GROWTH AND THE CRITICAL PERIOD OF WEED CONTROL

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Abstract

Climate change challenges crop production, driving rising temperatures and extreme weather events. Additionally, increased atmospheric CO_2 alters competitive dynamics between crops and weeds. While previous research has examined individual plant responses to elevated CO_2, its direct impact on weed management recommendations remains understudied. To address this knowledge gap, we assessed how elevated CO_2 influences the critical period of weed control (CPWC). Using radish (*Raphanus sativus* L.) as a model crop with dual use of above- and belowground parts for consumption and *Fagopyrum esculentum* Moench (buckwheat) as a model weed, we conducted growth chamber experiments evaluating CO_2 driven shifts in plant growth and CPWC duration.

Elevated CO_2 increased radish root biomass while shoot biomass remained relatively unchanged. In contrast, *F. esculentum* exhibited greater aboveground biomass allocation under elevated CO_2, while belowground biomass was unaffected. As a result, CPWC shifts under elevated CO_2 depended on the harvested plant part. For radish root yield, CPWC decreased by 93.46 growing degree days suggesting less time is required to manage weeds to sustain yields. Conversely, for radish leaf yield, CPWC increased, by 114.14 growing degree days, requiring a longer weed-free period.

These findings suggest that CO_2 driven shifts in biomass allocation could alter CPWC and weed management timing. Understanding these changes is critical for developing adaptive, climate-resilient weed management strategies.

Introduction

Anthropogenically driven climate change poses significant challenges to meeting global food demand through its impact on agroecosystems' functioning and services (Semeraro et al. 2023). It is widely agreed that accumulating atmospheric carbon dioxide (CO_2) creates new challenges to crop production by contributing to rising temperatures and extreme weather events (IPCC 2019). However, just as consequential but less readily assessed, increased atmospheric CO_2 modifies intra- and interspecific competitive interactions among plants (Patterson and Flint 1980; Ziska 2001). These shifts could directly impact existing weed management recommendations, a research area that, despite its importance, has been less explored.

The competitive interactions between crops and weeds are principally determined by the availability of resources. The more that weeds and crop resource demands and acquisition overlap, the higher the potential is for weeds to have a competitive impact on crops (Goldberg 1996; Wang et al. 2010). Notably, bigger weeds can remove a disproportionately larger proportion of resources, increasing their impact on crop yield in a process referred to as asymmetric competition (Freckelton and Watkinson, 2001). Asymmetric competition arises when individuals preemptively secure resources ahead of their competitors through early emergence, exhibiting a faster growth rate relative to their size, or overtopping (Weiner and Damgaard 2006). Various studies indicate that elevated CO_2 influences these competitive strategies depending on the functional traits present in the competing species (Ziska and Bunce 1993; Poorter and Navas 2002; Hampton et al. 2013). Consequently, elevated CO_2 can potentially mitigate or exacerbate asymmetric competition between weeds and crops. Despite various studies assessing the impact of CO_2 on crop and weed competition under high CO_2 concentration

(Brunce and Ziska 2000, Walthall et al. 2012, Korres et al. 2016), to our knowledge, no study has directly evaluated how weed management recommendations may change in response to CO_2 induced shifts in competition, a research need we explore here.

Evaluating weed-crop competition and applying ecological principles to manipulate interactions in favour of the crop is an integral component of sustainable weed management (MacLaren et al. 2020; Birthisel et al. 2021). A key metric for weed management recommendations is the critical period of weed control (CPWC), that is, the period during a crop's growth cycle when weeds must be removed to prevent yield loss (Nieto et al. 1968). Identifying the CPWC is a valuable tool that enables farmers to make informed decisions about when to implement weed management in order to maximise efficiency and minimise yield loss (Knezevic et al. 2002). The CPWC is determined by separately measuring two components of weed-crop competition: (1) the critical timing of weed removal (CTWR), or the maximum amount of time a crop can tolerate weed competition before experiencing unacceptable yield loss, and (2) the critical weed-free period (CWFP), or the duration a crop must remain weed-free to prevent significant reductions in yield.

Although studies have been conducted on the CPWC in various crops (Knezevic and Datta 2015; Ramesh et al. 2021; Zimdahl 2007), none have considered how it may shift under future climate projections, despite a growing need to understand how climate change influences weed crop competition (Birthisel et al. 2021). To fill this knowledge gap, we conducted a growth chamber experiment using radish (*Raphanus sativa* L.) as a model crop and *Fagopyrum esculentum* Moench (buckwheat) as a model weed to evaluate the impact of CO_2 on individual plant growth and the length of the CPWC. Specifically, we asked (1) How does atmospheric CO_2

modify plant growth, relative growth rate (RGR), and biomass allocation pattern of our model crop and weed species, and (2) Do these changes modify the length of the CPWC?

Materials and Methods

Experimental Design

We evaluated the effects of elevated CO_2 on individual plant growth and weed-crop competition in 2023 at Montana State University Plant Growth Center in Bozeman, MT, using two controlled environment growth chambers (Conviron 6050, model CMP6050, Controlled Environments Ltd., Winnipeg, Manitoba, Canada). One chamber was maintained at ambient CO_2 levels of 419ppm, while the other was set to 720ppm of CO_2 for elevated conditions, based on current and projected atmospheric CO_2 levels. The elevated CO_2 level was selected based on projections for the year 2100 under a high emissions scenario (SSP-8.5), as outlined in the IPCC Sixth Assessment Report (IPCC, 2023). CO_2 concentrations were regulated by supplying ambient air to one chamber and supplementing the other with additional CO_2 to maintain an elevated concentration of 720ppm and monitored daily via CO_2 sensors.

Chambers were randomly assigned to ambient or elevated CO_2 treatments for each trial to minimise chamber level effects. A total of three experimental trials were conducted over time for both the CPWC and growth trials, each serving as a true replicate of the CO_2 treatment to address potential pseudoreplication in the growth chamber experimental design (Porter *et al*. 2015; Rogers *et al*. 2021). In both chambers, day/night temperatures were set at 22°C and 18°C, respectively, with a photoperiod of 15/9 h and a measured light intensity of approximately 600 $\mu mol\ m^{-2}\ s^{-1}$ photosynthetically active radiation during the light period. These environmental settings were selected to simulate early summer conditions in Montana and align with the

recommended temperature and daylength range for optimal radish growth (Maynard and Houchmuth 2007).

Radish variety “French breakfast”, was selected as the model crop for its sensitivity to the length of the weed-crop competition period (Gibson and Liebman 2003; Harris et al. 2017) and its dual-purpose use of its above- and belowground parts for consumption (Gamba et al. 2021). *Fagopyrum esculentum* was selected as the model weed based on its fast, uniform emergence and growth under growth chamber conditions and its occurrence as a volunteer weed on organic vegetable farms in Montana (E. Kubinski, unpubl. obs.). Although not always a dominant weed in radish production systems, *F. esculentum* was prioritised for its ability to provide consistent and synchronous competitive pressure within the short 30-day growth period of radish. Plants were grown in pots (19 cm diameter x 15.2 cm deep) filled with potting soil mix containing Canadian Sphagnum Peat Moss, perlite, vermiculite, starter nutrient charge, wetting agent, and Dolomitic lime (Sunshine Mix #1, Sun Gro Horticulture Distribution Inc., Agawam, MA). Pots were watered daily for approximately 5 s using a watering can, and a soluble 20-10-20 fertiliser (Jack’s Professional General Purpose, J.R. Peters Inc., Allentown, PA) was applied weekly at a rate of 100ppm to maintain optimal growth conditions. Both individual growth plant analysis and evaluation of the CPWC adhered to the recommended growth duration for radish, spanning 30 days from planting to harvest (Botanical Interests 2025).

To address our first research question on the effects of CO_2 on plant growth, RGR, and biomass allocation patterns, individuals from each species were grown in competition-free conditions. Eight pots of an individual from each species were grown in the ambient and elevated CO_2 chambers and the whole study was repeated three times. Four individual plants per species

in each CO_2 treatment were randomly harvested at two different times: 15 days after planting or 30 days after planting. To assess the impact of CO_2 on RGR and biomass allocation patterns of radish and *F. esculentum*, their above- and below-ground biomass was collected at both harvest times. Fresh above- and below-ground biomass was collected for radish as the high-water content of the root prevented us from drying it without moulding. For *F. esculentum,* harvested biomass was dried to constant weight and weighed.

To answer our second question, we evaluated the impact of CO_2 on the CPWC by growing a single radish plant in the center of a 19 cm diameter x 15.2 cm deep pot, surrounded by 10 *F. esculentum* plants arranged in a circular pattern equidistant from the radish to reflect a high weed pressure scenario. Treatments included eight weedy and weed-free periods applied in both elevated and ambient CO_2 chambers: weedy and weed-free until harvest, weedy up to 10, 15, and 20 days post-emergence, and weed-free up to 10, 15, and 20 days post-emergence. Weeding treatments were applied to five separate pots (i.e., subsamples), randomly arranged in each growth chamber. Trials were carried out three times following Gibson and Liebman (2003), *F. esculentum* was added via direct seeding and removed by hand pulling at predetermined intervals to simulate field trials with weedy and weed-free plots. For weedy treatments, *F. esculentum* was planted at the same time as the radish and then removed at the designated time of removal. *Fagopyrum esculentum* was seeded 5 days before the specified “weed-free until” timing to ensure a synchronised emergence. At harvest, radish yield was quantified by weighing both below- and above-ground biomass. Additionally, we collected, dried, and weighed the above-ground biomass of *F. esculentum*.

Statistical Analysis

All statistical analyses were carried out using R, version 4.4.2 (R Development Core Team, 2024). To assess our first research question, the root and shoot biomass, the root-to-shoot ratio (RS), and RGR (Equation 1) of radish and *F. esculentum* were calculated in elevated and ambient CO_2 conditions.

$$RGR = \frac{\ln(W_2) - \ln(W_1)}{t_2 - t_1} \quad (1)$$

Where RGR = relative growth rate, ln = the natural logarithm, and W_1 and W_2 = the weight (grams) of the plant at times t_1 (15 days after planting) and t_2 (30 days after planting), respectively. Before any inferential statistics, the data was subjected to the Shapiro-Wilk Test to confirm normality and Levene's Test to verify homoscedasticity and ensure that the assumptions for conducting ANOVA were met. Subsequently, two-way ANOVAs were applied to root biomass, shoot biomass, RS, and RGR data to identify treatment effects and interactions, with Tukey's post-hoc pairwise comparisons when necessary. To assess results across trials while accounting for growth chamber variability, we fit linear mixed-effects models using nlme package (Pinherio *et al.*, 2025) for above and belowground biomass, RGR, and RS with fixed effects of CO_2 treatments, species, and their interaction, and Trial included as a random effect. Estimated marginal means (EMMs; a.k.a least-squares means) averaged over trail and their 95% confidence intervals were obtained using emmeans package (Lenth 2024), with Tukey adjustment for Treatment x Species comparisons.

To answer our second research question, and following methodology proposed in Knezevic et al. (2002) and Knezevic and Datta (2015) we estimated the CPWC for the above and belowground growth. The mean radish yields across treatment subsamples in each CO_2 condition

were converted to a relative yield percentage based on the mean season-long weed-free treatment. These yield values reflect radish response to varying durations of competition with *F. esculentum.* The duration of the CPWC was evaluated with relative yield regressed against growing degree days (GDD) accumulated from crop emergence. GDD was calculated using a base temperature of 5°C, consistent with previous research on radish and other *Brassicaceae* crops (Ackroyd 2015). For the analysis, we utilised the medrm() function in the medrc package (Ritz et al. 2015) to fit a four-parameter log-logistic nonlinear mixed-effects model, and we modelled weedy and weed-free curves separately for each CO_2 treatment and for both aboveground and belowground biomass. The following log-logistic model (Equation 2) was used:

$$Y = [C + (D - C)] / \{1 + \exp[B(\log X - \log E)]\} \quad (2)$$

where Y=relative response of the studied variable (percentage relative yield of the season-long weed-free response), C=lower limit, D=upper limit, X=time expressed in GDD, E=GDD giving a 50% response between the upper and lower limits, and B = slope of the line at the inflection point. Trial was modelled as a random effect inflection point (E) parameter to account for temporal and/or chamber variability across replication trials and lower/upper limits were fixed at 0 and 100. To determine the beginning and end of the CPWC, a 5% acceptable yield loss was applied to the model. We used the ED() function to extract ED5 from the weedy curve for the start of the CPWC and ED95 values from the weed free curve for the end. We considered differences in ambient and elevated CO_2 conditions to be different if estimates and standard errors did not overlap. Predicted value and fitted dose response curves were visualized using predict() and ggplot2.

Results

Impact of CO_2 on Relative Growth Rate (RGR), Plant Growth, and Biomass Allocation.

Elevated CO_2 did not influence changes in RGR ($p = 0.96$). Alternatively, CO_2 levels influenced biomass production and allocation, and effects differed by species for both aboveground biomass (Treatment x Species, $p = 0.016$) and belowground biomass ($p = 0.011$) (Figure 1). For *F. esculentum*, elevated CO_2 concentrations led to an increase in aboveground biomass ($p < 0.001$) with no difference belowground biomass ($p = 0.99$). Conversely, radish showed the opposite trend, with increased belowground biomass when exposed to elevated CO_2 ($p < 0.001$) but no change in aboveground parts ($p = 0.89$), indicating an increased investment in root development under elevated CO_2 conditions.

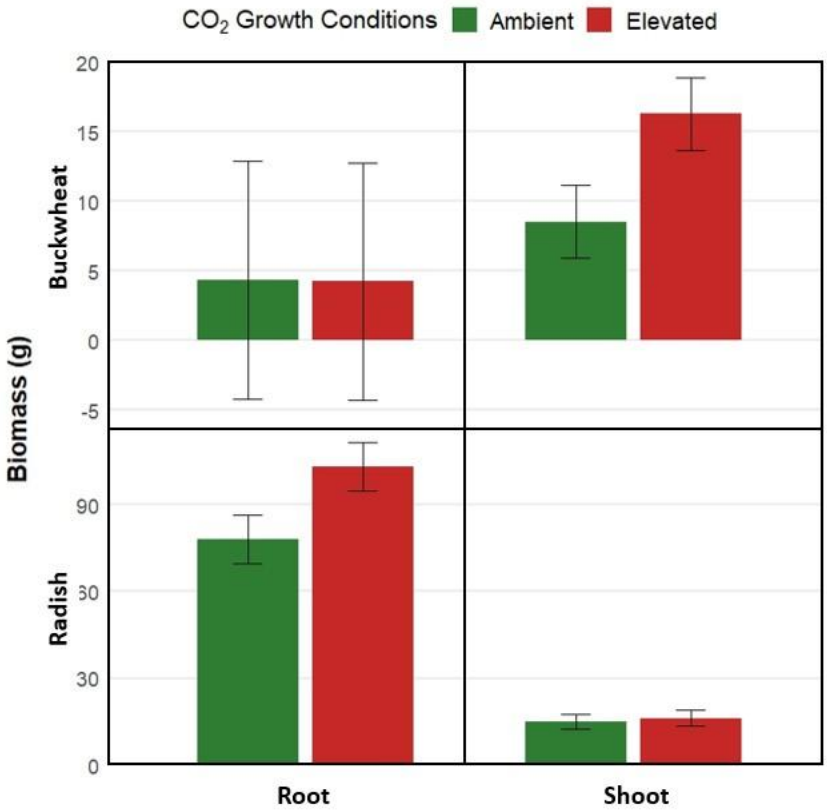


Figure 1: Above and belowground biomass of radish and *Fagopyrum esculentum* grown under ambient and elevated CO_2 concentrations. Under elevated CO_2 conditions, the aboveground biomass of *F. esculentum* increased ($p < 0.001$) while the belowground growth of radish decreased ($p < 0.001$).

Changes in RS of radish and *F. esculentum* further helped to evaluate differential biomass allocation patterns under ambient and elevated CO_2 conditions (Figure 2). RS showed strong differences between species ($p < 0.001$) but had no overall Treatment effect ($p = 0.12$). In *F. esculentum,* the RS ratio was ~47% lower under elevated CO_2 than ambient conditions; however, the large variability observed across trials precluded us from determining significant differences ($p = 0.12$). In contrast, radish exhibited a trend toward increased RS, increasing by ~23% under elevated CO_2 conditions, indicating greater allocation to root development; however, there was a lack of evidence for a significant difference between CO_2 treatments ($p = 0.16$).

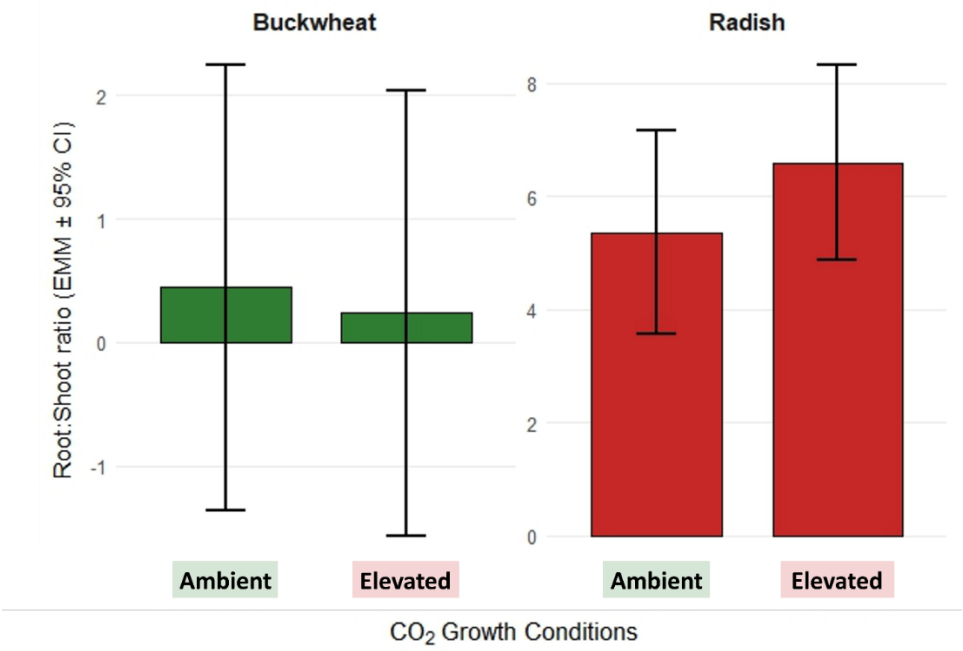


Figure 2: Root:Shoot ratio of radish and *F. esculentum* under ambient and elevated CO_2 conditions. Root:Shoot ratio for *F. esculentum* and radish did not differ across CO_2 treatments (p = 0.12 and 0.16, respectively).

Impact of CO_2 on the Length of the Critical Period of Weed Control

The duration of competition from *F. esculentum* impacted both belowground yield (Figure 3) and aboveground yields of radish (Figure 4) ($p < 0.001$). CO_2 conditions differently impacted the above and belowground length of CPWC of radish. For the belowground biomass, the length of the CPWC was longer under ambient CO_2 levels than in elevated CO_2 conditions (Figure 5). Specifically, under ambient CO_2 conditions, the length of CPWC was 340.31 GDD (148.38 ± 12.7 - 488.687 ± 56.9) and in elevated CO_2 conditions 246.85 GDD (136.41 ± 16.69 - 382.49 ± 46.24).

Alternatively, when examining the aboveground biomass of *R. sativus*, elevated CO_2 increased the length of the CPWC (Figure 6). The CPWC increased from 113.44 GDD (162.28 ±

21.21 - 382.5 ± 46.24) under ambient conditions to 227.85 GDD (170.64 ± 20.95 - 398.49 ± 73.19) under elevated conditions.

In addition to an increase in belowground biomass in radish under elevated CO_2 conditions, we saw an increase in *F. esculentum* aboveground biomass ($p > 0.001$). In weedy season-long pots and under elevated CO_2 conditions, *F. esculentum* aboveground biomass increased by 7.6% compared to those growing in ambient conditions.

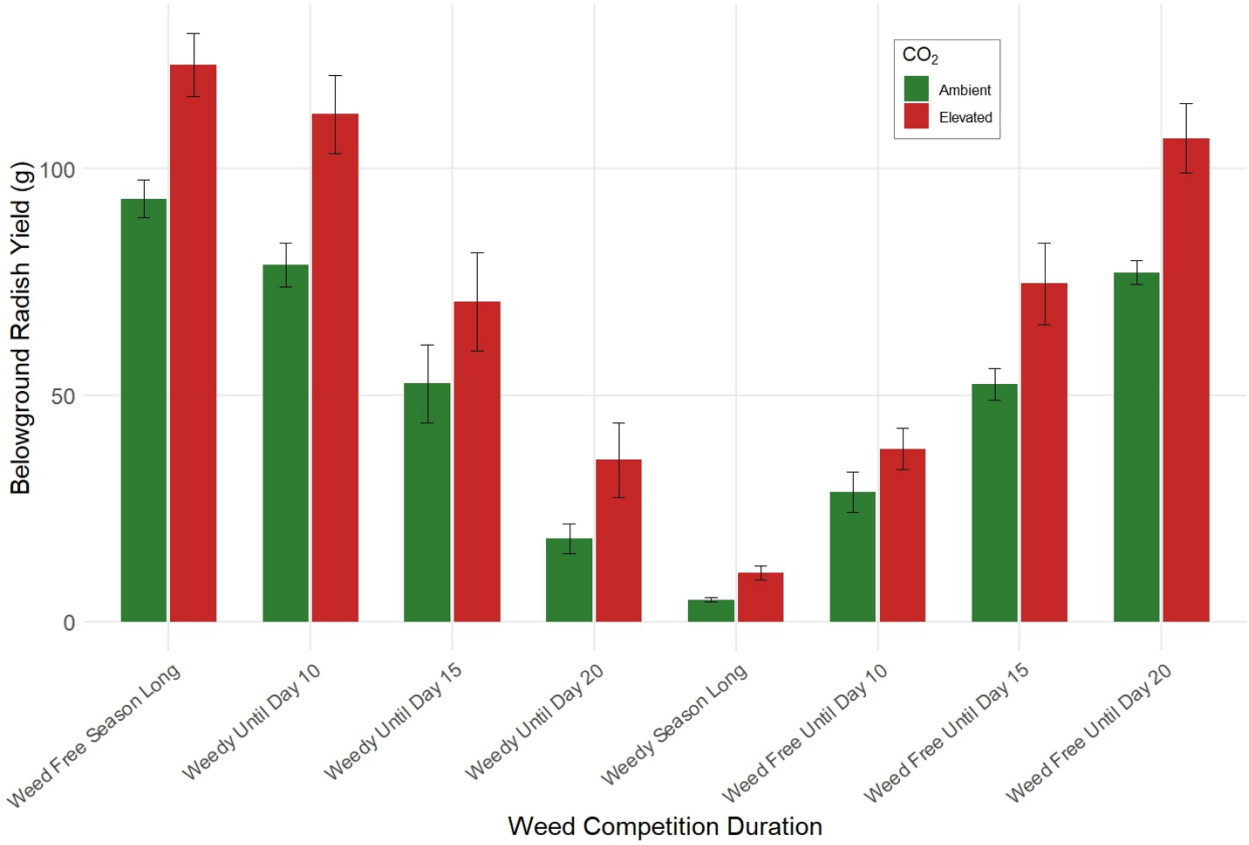


Figure 3: Impact of different durations of weed competition from *F. esculentum* on the belowground yield of radish under ambient and elevated CO_2 conditions.

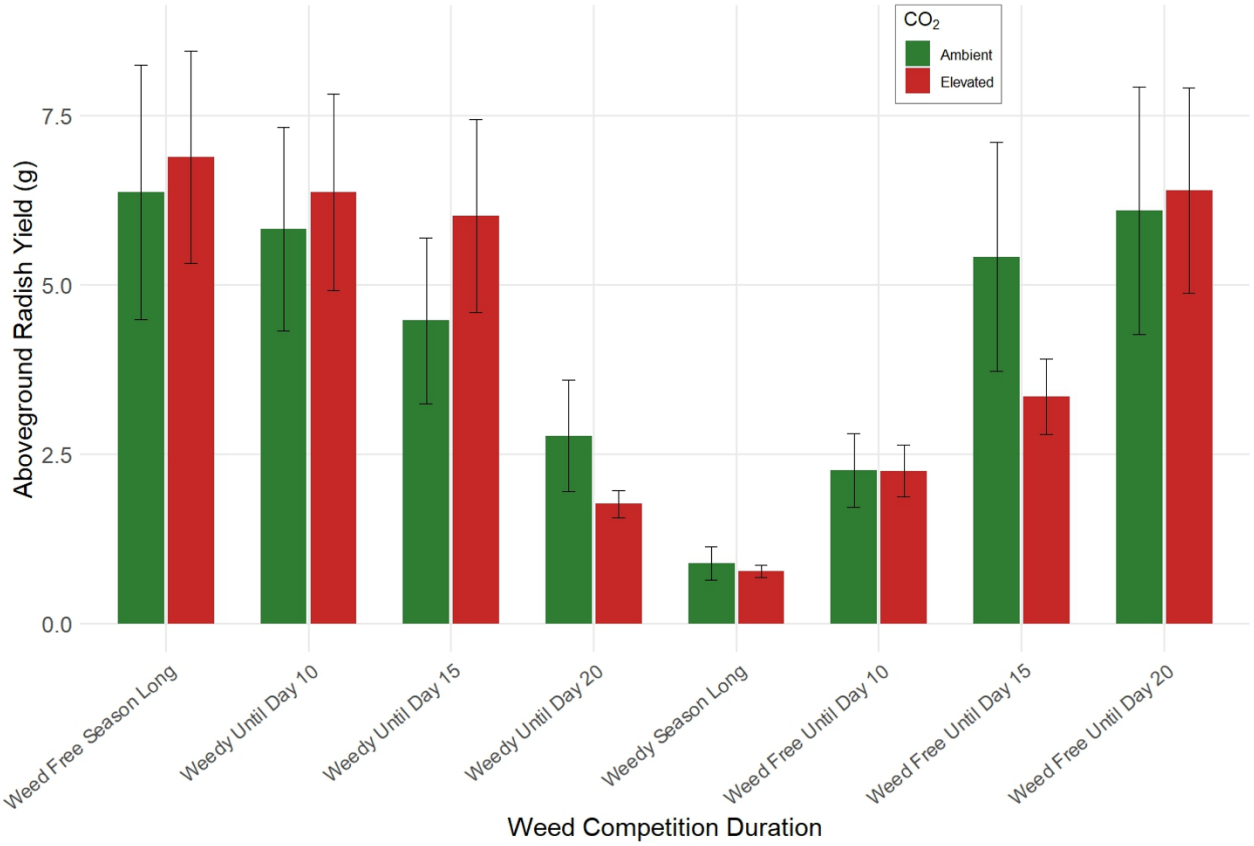


Figure 4: Impact of different durations of weed competition from *F. esculentum* on the aboveground yield of radish under ambient and elevated CO_2 concentrations.

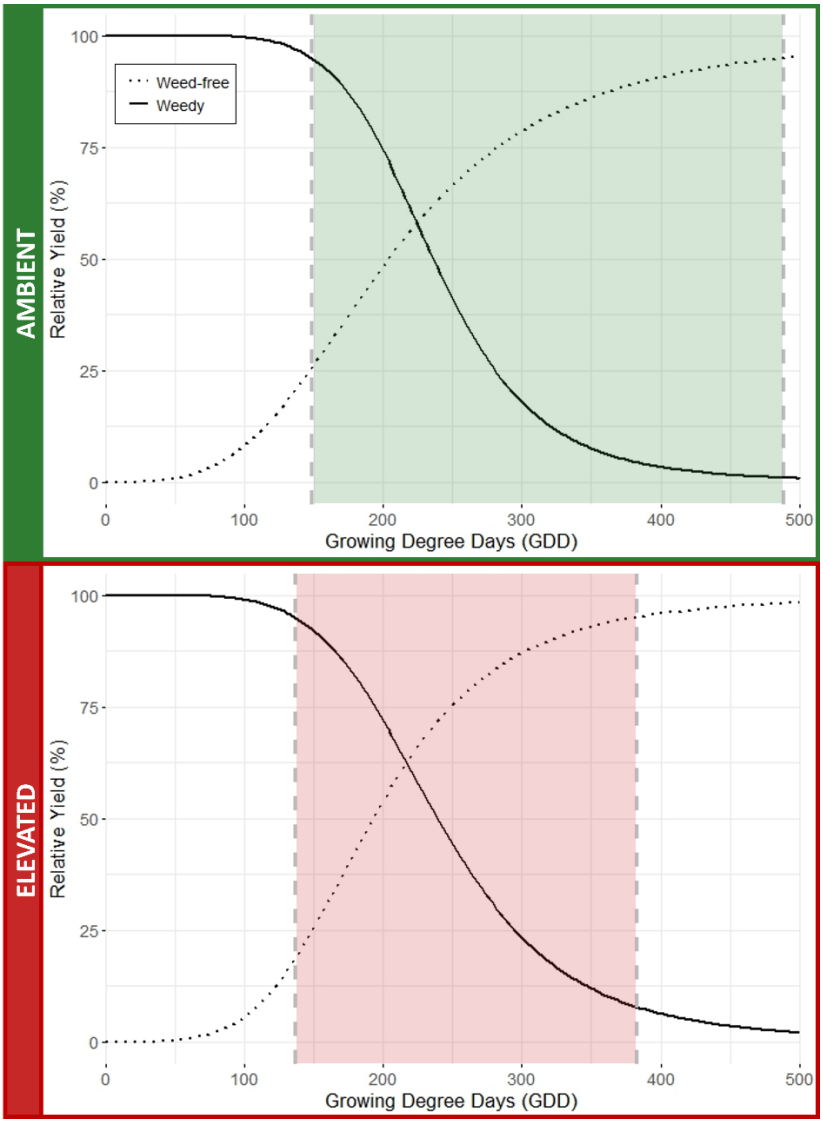


Figure 5: CPWC of radish belowground yields in ambient (top) and elevated CO_2 conditions (bottom). Elevated CO_2 conditions decreased the length of the belowground CPWC of *R. sativus*. The length of the CPWC decreased from 340.31 GDD (148.38 ± 12.7 to 488.69 ± 56.9) under ambient CO_2 conditions to 246.09 GDD (136.41 ± 16.69 to 382.49 ± 46.24) in elevated CO_2 conditions.

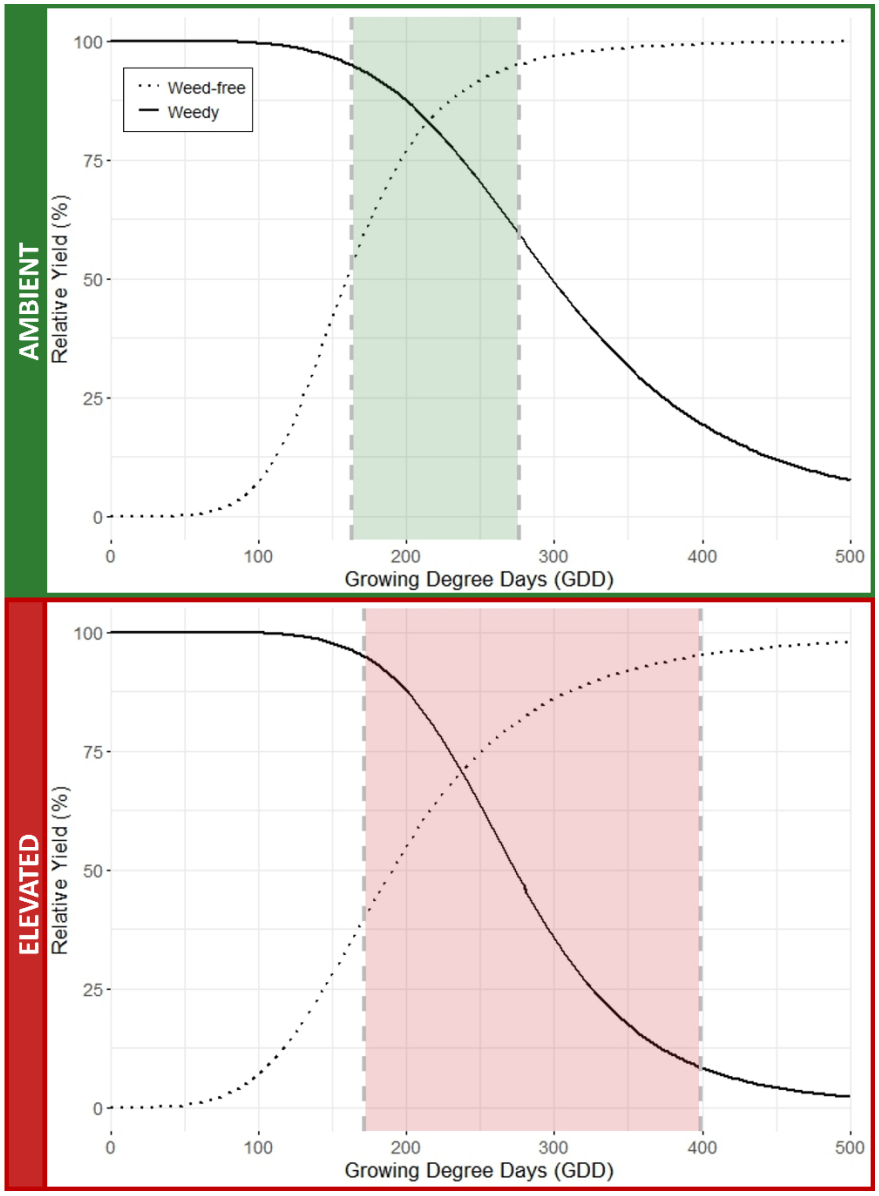


Figure 6: CPWC of radish aboveground yields in ambient (top) and elevated CO_2 conditions (bottom). The CPWC increased from 113.44 GDD (162.28 ± 21,207 to 275.72 ± 38.88) under ambient CO_2 conditions to 227.85 GDD (170.64 ± 20.95 to 398.49 ± 73.19) under elevated CO_2 conditions.

Discussion

This study highlights the interplay between rising CO_2 concentrations, plant growth dynamics, and competitive interactions, offering critical insights for refining weed management

recommendations in a changing climate. In addressing the first research question regarding the effects of elevated CO_2 on plant growth, we found that in the two studied species, although total biomass increased, RGR remained unchanged. Notably, it is plausible that differences in growth rate occurred earlier in development (i.e., between 0 and 15 days), prior to RGR data collection. As C_3 species, radish and *F. esculentum* respond to elevated CO_2 by increasing photosynthetic rates, leading to greater carbohydrate production (Drake et al. 1997). However, the utilization of this excess carbon for new growth (i.e., new plant organs) may be constrained, with preferential allocation to structural tissues such as thicker leaves or larger storage organs (Thomas and Harvey 1983; Paul and Foyer 2001; Ainsworth et al. 2004; Kirschbaum and Lambie 2015). As a result, there may be reductions in specific leaf area (SLA) and, consequently, a limited increase in RGR (Poorter and Navas 2003; Kirschbaum and Lambie 2015).

Species-specific differences in biomass allocation were observed under elevated CO_2, with radish prioritising belowground growth and *F. esculentum* allocating more biomass to aboveground structures. These contrasting responses are likely driven by differences in growth strategy and carbon sink strength. As a storage-root crop, radish possesses a strong belowground carbon sink where excess carbohydrates from elevated photosynthesis are preferentially stored in root tissues. Previous studies have reported similar patterns in radish, with increased belowground biomass under elevated CO_2, despite a decline in SLA (Barnes and Pfirrmann 1992; Usuda and Shimogawara 1998). In contrast, *F. esculentum* lacks a strong belowground storage organ, making it less likely to allocate surplus carbohydrates to root biomass. Instead, excess carbon was directed toward aboveground biomass accumulation, resulting in increased

shoot growth. This response aligns with previous findings that *F. esculentum* exhibits enhanced shoot biomass and stem elongation under elevated CO_2 conditions (Bernauer et al. 2024).

Our second research question assessed whether increased CO_2 levels impact the length of the CPWC. Our results indicate that while elevated CO_2 changed the duration of the CPWC in radish, the net impact depended on the desired plant part to be harvested. Under elevated CO_2 conditions, the CPWC for radish roots decreased, indicating that less weeding would be required to maintain an acceptable yield loss. This suggests that radish roots were less vulnerable to being impacted by competition from our model weed, *F. esculentum*. Alternatively, when looking at the leaf yield of radish, we saw an increase in the duration of the CPWC under elevated CO_2 conditions, therefore requiring more weeding to maintain an acceptable yield. These contradictory management recommendations underscore the challenges that predicted atmospheric conditions pose to weed management (Varanasi et al. 2016; Birthisel et al. 2021).

Differences in root and shoot biomass allocation patterns observed between radish and *F. esculentum* in response to CO_2 in growth trials may help explain the variable CPWC of radish. Under elevated CO_2, radish allocated more resources to belowground growth, producing larger roots. Because belowground growth is size symmetric (Schenk 2006), larger roots might have allowed the radish to better compete for belowground resources. Additionally, with increased root biomass, a greater yield loss was required to exceed the threshold for a 5% acceptable yield reduction. As a result, the length of the CPWC of radish roots was shorter when plants grew under elevated CO_2 conditions. The shift toward belowground biomass allocation in radishes under elevated CO_2 may help explain the longer CPWC observed for radish leaves, suggesting increased vulnerability to weed competition. While radish leaf biomass remained unchanged

under elevated CO_2, our model weed, *F. esculentum*, exhibited increased aboveground growth. Unlike belowground interactions, aboveground competition is typically asymmetric (Weiner & Damgaard 2006). Therefore, *F. esculentum*'s enhanced shoot growth likely conferred a competitive advantage over radish leaves.

It is important to acknowledge that the inferential space of our results is constrained by the specific species selected for this study. Notably, some weed species, such as *Cirsium arvense*, a perennial species that reproduces vegetatively via an extensive system of creeping roots, have been shown to increase root biomass under elevated CO_2 conditions (Ziska et al. 2004). If this weed was grown alongside radish, this could have intensified competition and extended the CPWC of the radish root. Additionally, while *F. esculentum* can be a volunteer weed on farms, it has been bred as a cover crop, potentially exhibiting lower genetic variability than other weedy species (Nosratti et al. 2023). Greater genetic diversity and plasticity in other weedy species may enhance their ability to adapt to rising atmospheric CO_2 levels (Clements and Jones 2021), further influencing competitive interactions and weed management outcomes.

Because the study was conducted in a controlled environment and focused on a single crop-weed interaction, the exact CPWC timings identified are unlikely to be directly transferable to field conditions, where environmental variability, management practices, and diverse weed communities interact. Furthermore, while we conducted three experimental trials with CO_2 treatments randomly assigned to growth chambers, we recognize that some residual variation between growth chambers may persist (Porter et al. 2015; Rogers et al. 2021). However, we expect the directional trends we observed - a shortened CPWC for root yield and a lengthened CPWC for shoot yield under elevated CO_2, to remain consistent under field scenarios for root

crops like radish where above and belowground harvestable organs differ in their response to elevated CO_2 and vulnerability to competition.

Our findings emphasise the increasing complexity of weed management under anthropogenic climate change. Rising atmospheric CO_2 has been shown to reduce herbicide efficacy through several morphological and physiological changes in weeds, including increased leaf thickness, altered cuticular wax composition, reduced stomatal density, and greater root:shoot allocation, all of which can limit herbicide absorption, translocation, or concentration at the target site (Ziska 2016). Additionally, mechanistic evidence suggests that under elevated CO_2 and temperature, glyphosate was translocated more rapidly from treated leaves to carbon sinks like the shoot meristems and roots compared to plants in ambient conditions resulting in reduced weed sensitivity to the herbicide (Matzrafi et al. 2019). Other research shows that elevated CO_2 can indirectly reduce herbicide effectiveness by enhancing weed biomass accumulation and growth rates; therefore, reducing the concentration of herbicides within plant tissues (Cowie et al. 2020). In addition to altered weed response to herbicides, elevated CO_2 has also been found to increase the growth and productivity of weeds, suggesting weeds will become more competitive (Bajwa et al. 2019; Jabran and Doğan 2020). Although changes in herbicide sensitivity and growth have been found to be species-dependent (Waryszack et al. 2018), findings on physiological and phenological shifts in weeds due to elevated CO_2 could effectively narrow the window of management, mirroring changes in the timing of the CPWC. Collectively, these trends suggest that both the timing and efficacy of weed management, whether chemical or mechanical, will require reassessment in future agroecosystem climates.

Overall, our results suggest that future climate change projections will impact the CPWC of crops, but the result will likely be dependent on specific characteristics of the crop-weed systems. Furthermore, predicting changes in the duration of CPWC will be especially challenging for producers of crops like radish, where both the above and belowground parts are harvested, given the opposite impacts on above and belowground plant yields. Because the CPWC characterizes the period when the crop is most vulnerable to competition, climate-induced shifts in crop-weed interactions suggest potential changes to other management practices like timing of cover crop plantings, intercropping, row spacing, and fertilizer placement (Swanton et al. 2015; Birthisel et al. 2021), underscoring the necessity of developing adaptive tactics to support sustainable agricultural systems (Altieri et al. 2025).

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CHAPTER FOUR

WEED COMMUNITIES ON ORGANIC VEGETABLE FARMS IN MONTANA: TRAIT-BASED PATTERNS ACROSS FARMS, CROPS, AND YEARS

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Abstract

Increased understanding of the factors determining the abundance of weeds is an essential component of ecologically-based management. Trait-based approaches provide a mechanistic framework for this by linking species composition to ecological strategies that determine how weeds establish, persist, and compete. Despite this importance, most research has focused on large-scale field crops, with limited work in diversified organic vegetable systems. This gap is particularly pronounced in the Middle Rockies, where little information exists on weed community composition, and where short growing seasons and high climatic variability may limit the applicability of findings from other regions.

This study evaluated how farm, crop, and year influence weed communities and functional traits on organic vegetable farms in Montana. Field surveys were conducted across six diversified organic farms during the 2022 and 2023 growing seasons, including four crops (beans, carrots, kale, and onions). Weed species aboveground biomass was quantified at peak biomass. Functional composition was characterized using community-weighted mean (CWM) traits representing leaf economic spectrum, phenological, reproductive, and whole-plant strategies. Differences in functional composition were assessed using principal components analysis and PERMANOVA, and the relative influence of farm, crop, and year on individual traits was evaluated using linear models.

A total of 46 species were identified, with communities characterized by low evenness and strong dominance of a few species, with the three most abundant species accounting for over 45% of total biomass. Functional composition differed among farms and between years, while crop identity had little effect. Across traits, farm consistently explained the greatest proportion of

variation. Functional diversity metrics showed weaker responses, with functional richness varying among farms and Rao's quadratic entropy differing between years.

Our results indicate that weed community assembly in organic vegetable systems is primarily structured at the farm scale, with limited evidence for crop-level filtering. Thus, farm-level management strategies may be the most effective to shape weed communities Together, these findings provide a foundation for understanding weed communities and their assembly in organic vegetable systems in the Middle Rockies and offer insights for guiding ecologically-based management recommendations.

Introduction

Weeds pose a major challenge to agricultural production (Oerke 2006), and this problem is often more pronounced in organic systems due to their inability to rely on synthetic herbicides. As a result, weeds are consistently identified as one of the primary constraints in organic production systems (Jerkins and Ory 2016). Compared to conventional systems, organic production typically has greater weed abundance and diversity (Edesi et al. 2012; Graziani et al. 2012; Mwangi et al. 2024) and requires higher labor inputs for weed management (Crowder and Reganold 2015). These challenges are further intensified in vegetable systems, where many crops have inherently low competitive ability (Van Heemst 1985) and require longer periods of weed management to maintain acceptable yields and quality (Knezevic et al. 2002; Ramesh et al. 2022). On diversified organic vegetable farms, these challenges are further amplified by the need to simultaneously manage multiple crops, each with differing phenologies and management requirements.

Traditionally, weed management has prioritized minimizing weed abundance, regardless of species identity. However, achieving this goal in organic systems has led to an over-reliance on intensive tillage and manual control, which can degrade soil health (Balesdent 2000) and require substantial labor inputs (Crowder and Reganold 2015). At the same time, weeds can provide important ecosystem services, including improving soil health (Brito et al. 2013; Moreau et al. 2020; Sarathambal et al. 2014) and supplying resources for wildlife, pollinators, and natural enemies (Balfour and Ratnieks 2022; Barbercheck and Wallace 2021; Marshall et al. 2003). Greater weed diversity may also mitigate crop-weed competition by increasing resource partitioning among weed species and reducing the relative dominance of highly competitive ones (Adeux et al. 2019*;* Smith et al. 2010; Storkey and Neve 2018). Therefore, to address the trade-offs between the costs of management and the unintended consequences of weed suppression, it is essential to develop ecological weed management tactics that rely on biological processes rather than on off-farm inputs. Two frameworks can help us achieve this goal: community assembly and trait-based analysis.

Community assembly provides a framework for understanding how weed communities are shaped through interacting dispersal and selection processes (Booth and Swanton, 2002). This theory proposes that species composition within a community is determined by a series of filters that determine whether a plant can colonize, establish, and persist at a certain time and place through interacting processes operating across multiple spatial and management scales (Diamond 1975; Keddy 1992; Weiher and Keddy 1999). In agroecosystems, these filters include dispersal processes, temporal variation, environmental conditions, biotic interactions, and, importantly, management practices (Belyea and Lancaster 1999; Booth and Swanton 2002).

While weed communities are shaped by interacting processes operating across year, farm, and crop scales, these responses are ultimately driven by differences in functional traits (Gaba et al. 2017). Functional traits are measurable characteristics that influence how a species grows, reproduces, and interacts with its environment; therefore, determining its ability to establish and persist in a particular environment (Lavorel and Garnier 2002). In addition to shaping species' responses to management, functional traits also determine how they influence ecosystem processes, including resource use and competition with crops, plant soil-feedbacks, and the provision of ecosystem services (Bárberi et al. 2018; Miller and Menalled 2015; Navas 2012). Consequently, a trait-based approach to weed community analysis provides a mechanistic framework for linking species composition and assembly with biomass accumulation and competitive dynamics.

Despite the importance of understanding weed communities for informing management recommendations, there remains a lack of research in organic vegetable systems as most studies have been conducted in field crop systems (Adeux et al. 2019; Derrouch et al. 2022; Edesi et al. 2012; Leoni et al. 2026). Further, those studies focused on vegetable systems are largely limited to the northeastern United States and Europe (Buchanan et al. 2014; Ciaccia et al. 2020; Ciaccia et al. 2025; Mohler et al. 2018; Jernigan et al. 2017; Testani et al. 2019). This represents a critical knowledge gap for the Middle Rockies, including Montana, where organic vegetable production occurs under short growing seasons and high climatic variability limiting the applicability of results from other regions. To the authors' knowledge, there are no previous studies formally characterizing functional traits of weed communities on organic vegetable farms in this region. To address this gap, this study evaluated how year, farm, and crop type influence weed

communities and functional traits. We expected weed communities to differ among farms due to their inherent variation in environmental conditions, management histories, and practices, and among crops due to differences in crop traits and associated crop-specific management, all factors that influences weed community assembly.

Materials and Methods

Field Methods

Field surveys were conducted across six different organic, diversified vegetable farms during the 2022 and 2023 growing seasons. These farms were located across two vegetable producing areas in the state of Montana; the Bitterroot and Gallatin valleys. All farms surveyed were managed using USDA certified organic practices, including mechanical cultivation and hand weeding, although management intensity and timing varied among farms (Table 1). Within each farm, four crops; beans (*Phaseolus vulgaris*), carrots (*Daucus carota*), kale (*Brassica oleracea*), and onions (*Allium cepa*) were selected based on differences in growth form, establishment strategy, and competitive ability. Kale is a predominately transplanted brassica in Montana with rapid canopy development and has relatively high competitive ability compared to the other vegetable crops evaluated (VanHeemst 1985; Welbank 1963). Beans are moderately competitive, direct-seeded legumes with moderate canopy development and the ability to fix nitrogen, potentially altering resource availability (Galon et al. 2017; Karavidas et al. 2022; Van Heemst 1985). Carrots are slow-growing, direct-seeded crops with limited competitiveness, often resulting in prolonged periods of weed susceptibility (Colquhoun et al. 2020; Swanton et al. 2010, Kubinski et al. in press). Onions are shallow-rooted, slow-growing, and weak competitors with limited canopy closure, making them highly sensitive to weed pressure (Qasem 2016;

VanHeemst 1985). Together, these farms and crops represent a gradient of ecological conditions and management regimes that have the potential to influence weed community assembly.

Weed communities were sampled during peak weed biomass (late July to early August), corresponding to mid- to late-season crop development. Mean temperature and total precipitation during the growing season were obtained for each region and year from local weather stations to characterize interannual and regional climatic variation. Soil samples were collected within each crop row at each farm to characterize edaphic conditions associated with weed community composition. In each crop field, three soil cores were collected and separated by depth (0-6 cm and 6-24 cm). Cores from the same depth were combined to provide a representative sample for each depth within each field. Samples were homogenized in the field prior to submission to an independent laboratory for analysis. Soil properties measured included pH and nitrate at both depths, as well as organic matter content and extractable phosphorus (P), potassium (K), and zinc (Zn).

Within each crop, a representative crop row was selected within a single field. A 10-m transect was established parallel to the crop row. Along each transect, five quadrats (0.5 m × 0.2 m) were placed at 0.5-m intervals within the crop row with quadrat locations along the transect randomized to reduce spatial bias. The crop row was centered within each quadrat to ensure consistent sampling of within-row weed communities. Within each quadrat, all weed individuals were identified to species level and aboveground biomass was clipped at the soil surface, sorted by species (or species group), dried, and weighed to determine species-level and total biomass (g m^{-2}).

Prior to data collection, all surveyors were trained to ensure consistency in species identification and counting. Species identification was conducted using regional field guides and online resources; when necessary, specimens were collected and submitted to the Montana State University Schutter Diagnostic Lab for confirmation. Due to challenges associated with identifying seedlings, many of which were only distinguishable at the cotyledon stage, and some taxa were grouped during identification. Specifically, *Chenopodium album* L. and *Chenopodium glaucum* L. were combined, as were species within the genus *Amaranthus* and members of the sowthistle complex (*Sonchus* spp.). These groupings were applied consistently across all samples and reflect both identification limitations at early growth stages and functional similarity among taxa. Additionally, *Equisetum arvense* was excluded from this trait-based analyses because its spore-based reproductive strategy and distinct life history limiting comparability with the seed-producing species included in this study, and it contributed >1% to overall abundance.

Table 1: Characteristics of sampled organic vegetable farms and growing season conditions across regions and years. Soil properties represent farm-level averages across crops at 0-6 cm depth. Mean temperature and total precipitation were calculated for each region and year from May 1 through August 1. Additional farm characteristics and detailed soil measurements by crop and depth are provided in Supplemental Table 1

Farm	Region	Year	Farm size (ac)	Years farmed	Soil pH	OM (%)	Nitrate (ppm)	Temp (°C)	Precip (mm)
Farm 1	Gallatin	2022	5-9.9	5-9	7.3	5.13	11.4	15.2	184
		2023	5-9.9	5-9	6.88	6.6	20.3	15.9	173
Farm 2	Gallatin	2022	>1	1-4	7.28	6.48	32.3	15.2	184
		2023	>1	1-4	7.5	5.65	31.8	15.9	173
Farm 3	Gallatin	2022	1-4.9	5-9	7.2	4.95	22.5	15.2	184
		2023	1-4.9	5-9	7.4	6.15	35.8	15.9	173
Farm 4	Bitterroot	2022	5-9.9	20+	8.2	5.73	20.5	15.2	309
		2023	5-9.9	20+	8	6.55	59.8	18	96
Farm 5	Gallatin	2022	5-9.9	10-19	7.63	3.5	28.8	15.2	184
		2023	5-9.9	10-19	6.98	5.1	56.5	15.9	173
Farm 6	Bitterroot	2022	5-9.9	10-19	7.85	2.85	10.5	15.2	309
		2023	5-9.9	10-19	7.8	3.93	18.5	18	96

Data Analysis

Weed biomass from the five plots (subsamples) per crop was pooled prior to the analysis. To provide species-level context for weed community composition, relative biomass was calculated across all sampling units and scales (i.e. crop, farm, and year). Total biomass and abundance were then summed for each species across all scales sampled, and their relative biomass values were calculated by dividing species totals by the overall community total. Species were subsequently ranked by their relative biomass to characterize dominance patterns within the weed community, and the top-ranked species were visualized to illustrate community structure.

Weed communities and associated traits were compared across spatial (i.e., crops and farms) and temporal (i.e., years) gradients. Data was analyzed using a trait-based approach (Navas 2012). Traits were selected to represent a range of strategies associated with weed

persistence and ecological functions (Table 2). Most of the species-level trait data were compiled from the TRY (Kattge et al. 2011) and the LEDA databases (Kleyer et al. 2008). We used peer-reviewed literature and extension resources to obtain trait values that were missing in the TRY and LEDA databases (See Supplemental Table 2). Traits included both continuous and categorical variables. For seed bank longevity, we used Grime's classification to rank the categories (i.e., 1; transient, 2; short-term persistent, and 3; long-term persistent) and the ordinal variable was then included alongside continuous traits in the analysis. Continuous traits were standardized (mean = 0, SD = 1) prior to analysis, and categorical traits were converted to binary variables to allow inclusion in multivariate analyses.

Community-level trait composition was quantified using biomass community-weighted means (CWM) traits, with species contributions weighted by their relative biomass within each community. For categorical traits, biomass-weighted proportions were calculated to represent the relative contribution of each trait within communities. This approach emphasizes the influence of species based on their dominance, providing a functional representation of community composition in agroecosystems. While CWM values for numerical traits were calculated using the functcomp() function of the 'FD' package (Laliberté and Legendre 2010; Laliberté et al. 2014), categorical trait composition was computed by multiplying the relative biomass by the corresponding trait matrix.

Functional diversity was quantified using biomass-based community data and species trait information with the dbFD() function of the 'FD' package (Laliberté et al. 2023). Indices included functional richness (FRic), functional evenness (FEve), functional divergence (FDiv), Rao's quadratic entropy (RaoQ), and functional dispersion (FDis). The effects of crop, farm, and

year on each functional diversity metric were evaluated using linear models followed by ANOVA, with models specified as FD metric ~ crop + farm + year. Model assumptions were assessed using residual diagnostics. All analyses were conducted in R (R Core Team 2024), and data visualization was performed using the ggplot2 package (Wickham et al. 2016).

Patterns in functional trait composition were visualized using principal coordinates analysis (PCoA) conducted on a Gower dissimilarity matrix, which allows for the integration of both continuous and categorical trait data. The Gower distance matrix was calculated from the combined CWM trait matrix using the daisy() function of the 'cluster' package (Maechler et al. 2026), and ordination was performed using the cmdscale() function. The first two principal coordinate axes were retained for visualization and interpretation. To aid in interpretation of the ordination, relationships between individual traits and ordination axes were assessed using the envfit() function in the 'vegan' package (Oksanen et al. 2001). Traits were ranked based on their squared correlation coefficients (R^2) with the ordination, providing a measure of the strength of each trait's association with the primary gradients in functional composition (Legendre and Legendre 2012).

Differences in community-level trait composition across crops, farms, and years were evaluated using permutational multivariate analysis of variance (PERMANOVA) implemented with the adonis2() function of the 'vegan' package (Oksanen et al. 2001). Gower distance matrices were calculated from the combined CWM trait values, and significance was assessed using 9,999 permutations. The PERMANOVA model included crop, farm, and year as explanatory variables (distance ~ crop + farm + year), and marginal tests were used to evaluate the independent contribution of each factor. To further quantify the influence of these variables

on individual functional traits, linear models were fit for each CWM trait, with trait values specified as the response and crop, farm, and year as explanatory variables (Trait_CWM ~ crop + farm + year). The proportion of variance explained by each factor (partial R^2) was calculated from sums of squares derived from analysis of variance (ANOVA) tables, reflecting the strength of farm, crop, and year as drivers of individual traits. P-values were obtained from the corresponding ANOVA F-tests to evaluate the statistical significance of each factor, allowing comparison of both effect size and statistical support across traits.

Table 2: Functional traits used to characterize weed community composition, including trait functional group, trait acronym, description, data type, and associated ecological functions.

Functional group	Trait	Description	Type	Ecological function
Leaf Economic Spectrum Traits	SLA	Leaf area per unit dry mass	Continous	Rapid growth and resource capture
	Leaf N	Leaf nitrogen concentration	Continous	Photosynthetic capacity and growth potential
	LDMC	Dry mass per unit leaf fresh mass	Continous	Resource conservation and stress tolerance
Whole Plant Traits	RLF	Raunkiaer life form classification	Categorical	Regeneration strategy and disturbance response
	RT	Root type	Categorical	Early resource acquisition and establishment
	PH	Plant height	Continous	Light competition and canopy dominance
Reproductive Traits	REP	Reproductive Strategy	Categorical	Colonization ability and spread
	SBL	Seed bank longevity	Continous	Long-term persistence under disturbance
	SDM	Seed mass	Continous	Establishment vs dispersal tradeoff
Phenological Traits	ET	Emergence timing	Categorical	Temporal niche and crop interaction

Results

A total of 46 weed species were identified across all crops, farms, and years. Weed community composition was highly uneven, with a small number of species accounting for a large proportion of total biomass, alongside high species richness within the weed communities (Figure 1). *Sonchus oleraceus* was the most dominant species, contributing 18.8% of total biomass, followed *by Amaranthus retroflexus* (15.5%) and *Stellaria media* (11.0%). Together,

these three species accounted for over 45% of total community biomass. Additional dominant species included *Cirsium arvense* (7.7%), *Elymus repens* (6.5%), and *Chenopodium album* (5.5%). In contrast, 42 species occurred at relatively low abundance, with individual contributions below 5%, indicating a long tail of less dominant taxa (Supplemental Table 3).

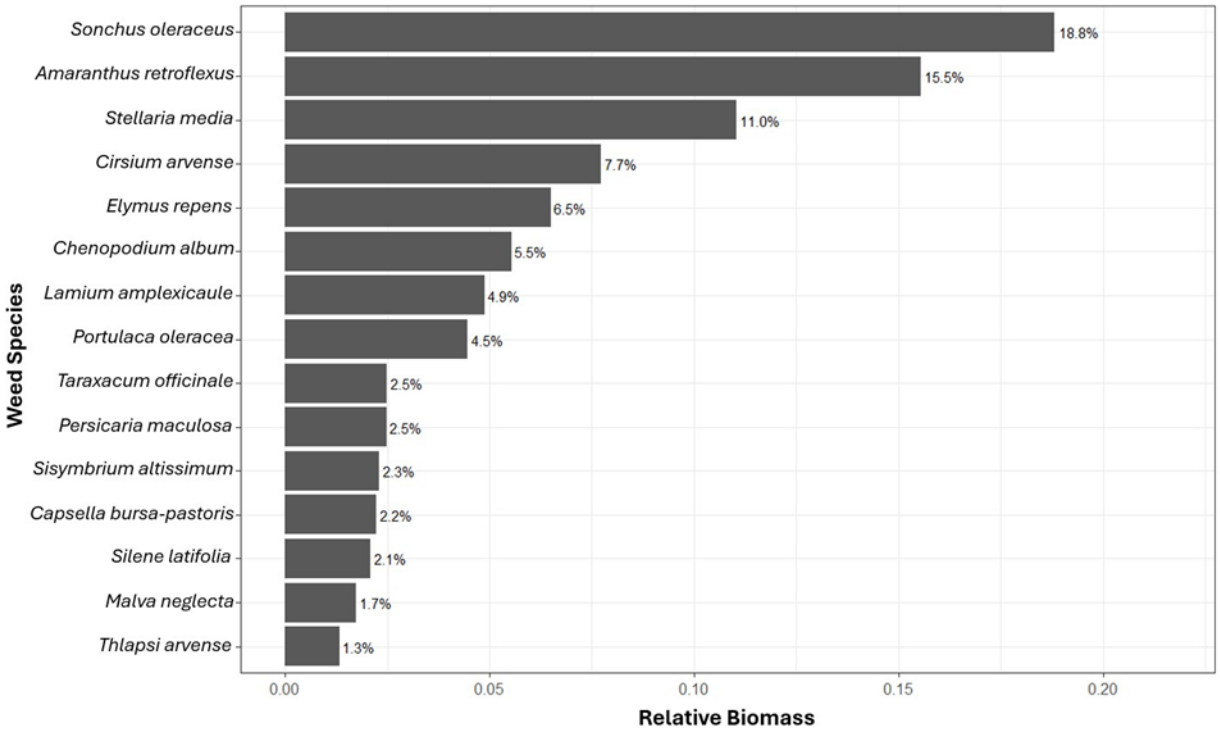


Figure 1: Relative biomass (%) of the 15 most abundant weed species across all farms, crops, and years. Species are ranked by their proportional contribution to total community biomass.

Functional diversity metrics showed a range of responses across scales. There was strong evidence that functional richness (FRic) varied among farms ($p < 0.001$) (Figure 2), indicating differences in the breadth of trait space occupied across sites, whereas there was marginal evidence for differences among crops ($p = 0.078$). Functional evenness (FEve) and functional divergence (FDiv) showed little evidence of variation across crop, farm, or year (all $p > 0.36$), suggesting relatively consistent distributions of biomass within trait space. In contrast, Rao's quadratic entropy (RaoQ) showed evidence of variation between years ($p = 0.048$), indicating

temporal shifts in overall trait dissimilarity among species within communities. Functional dispersion (FDis) showed weaker and more variable responses, with some evidence of differences among farms ($p = 0.038$).

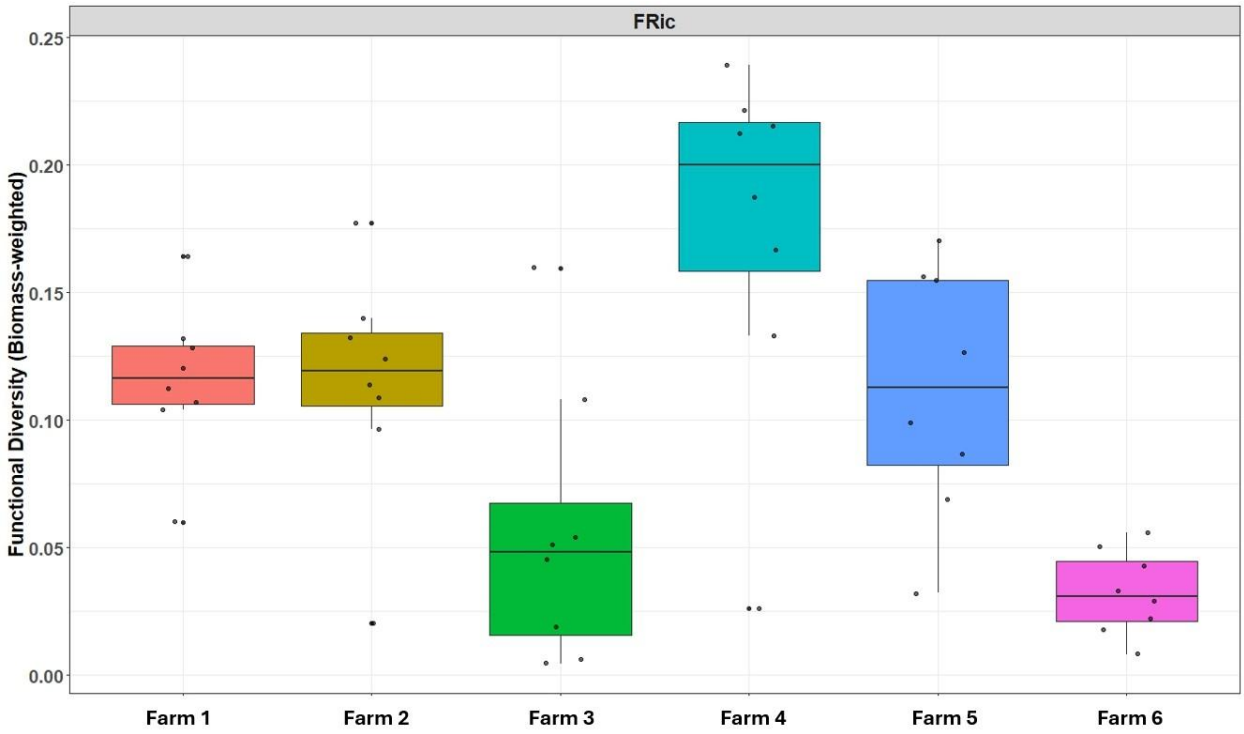


Figure 2: Functional richness (FRic) of weed communities within each farm, with points indicating individual observations. Functional richness varied among farms, with Farm 4 exhibiting the highest median FRic and Farms 3 and 6 showing comparatively lower values, indicating differences in the breadth of functional trait space occupied by weed communities across farm contexts.

Weed community functional composition varied among farms and between years, while little evidence was found for differences among crops. The PCoA of CWM trait values based on Gower distance captured a substantial proportion of variation in functional composition (PCoA1 = 45.2%, PCoA2 = 17.7%). The relative contribution of traits to the ordination space varied within and across functional categories, with leaf dry matter content, spring emergence,

vegetative reproduction, and therophyte life form among the most strongly associated traits, representing leaf, phenology, reproductive, and whole-plant categories, respectively (Figure 3).

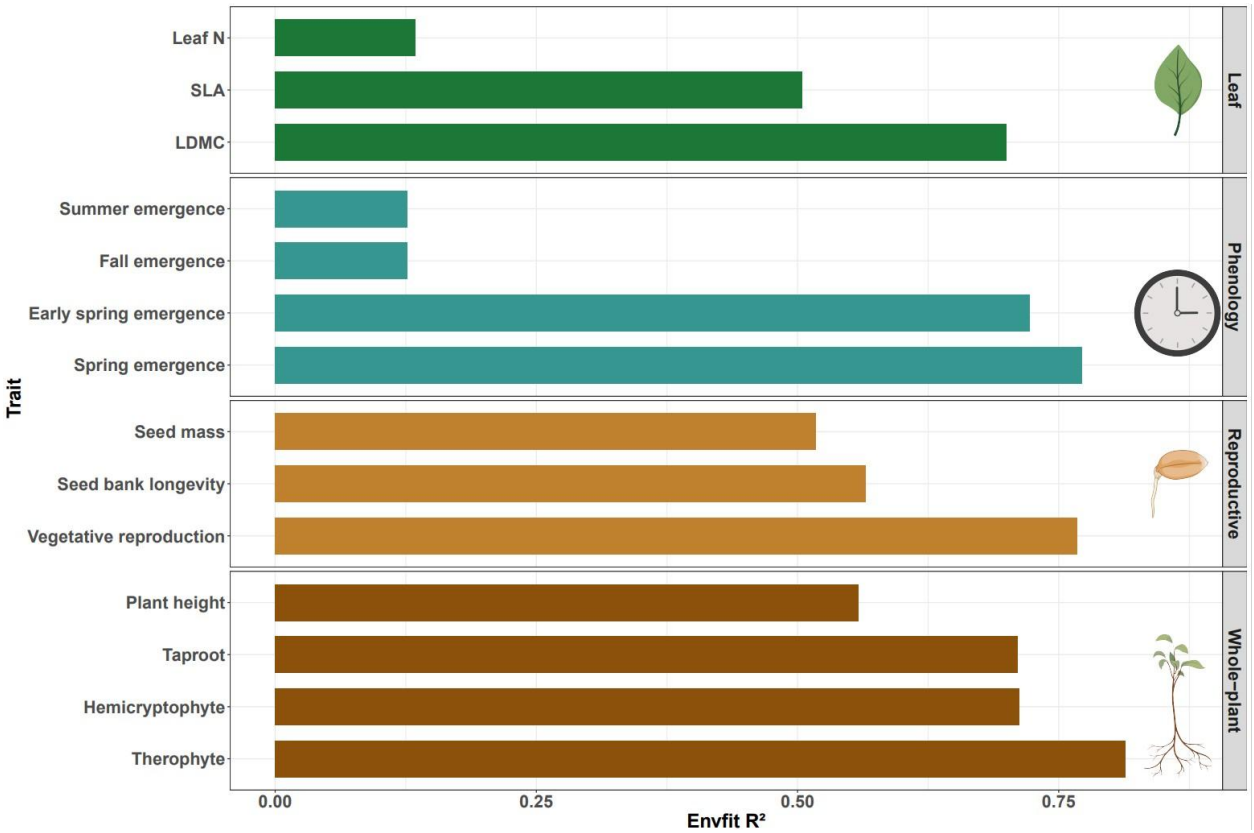


Figure 3: Relative contribution of functional traits to the primary axes of variation in weed community composition based on principal coordinates analysis (PCoA) using Gower distance. Values represent the squared correlation coefficients (R2) from envfit, indicating the strength of association between each trait and the ordination. Traits are grouped by functional category (leaf, phenology, reproductive, and whole-plant traits) to highlight their relative importance in structuring weed communities.

Across all communities, separation along PCoA1 reflected a gradient from annual, seed-based strategies to more persistent, vegetatively reproducing species. Communities with positive PC1 scores were associated with therophytes, greater seedbank longevity, and spring emergence, indicating a dominance of fast-growing, disturbance-adapted species. In contrast, negative PCoA1 scores were associated with hemicryptophytes, vegetative reproduction, higher LDMC,

and greater seed mass, reflecting more persistent, resource-conservative strategies. Variation along PCoA2 represented a secondary gradient in functional composition, associated with differences in resource-use and growth strategy traits, including specific leaf area (SLA), leaf nitrogen content, and emergence timing. However, separation along this axis was less pronounced than along PCoA1, indicating that these traits contributed to finer-scale variation among communities rather than the primary structuring gradient.

The PERMANOVA indicated strong evidence that farm explained variation in functional composition ($R^2 = 0.21$, $p = 0.007$; Figure 4). There was also evidence for an effect of year ($R^2 = 0.07$, $p = 0.010$; Figure 5), indicating temporal shifts in trait composition between sampling years. In contrast to our expectations, there was little evidence that crop identity explained variation in functional composition ($R^2 = 0.04$, $p = 0.697$; Figure 6), with substantial overlap among crop types.

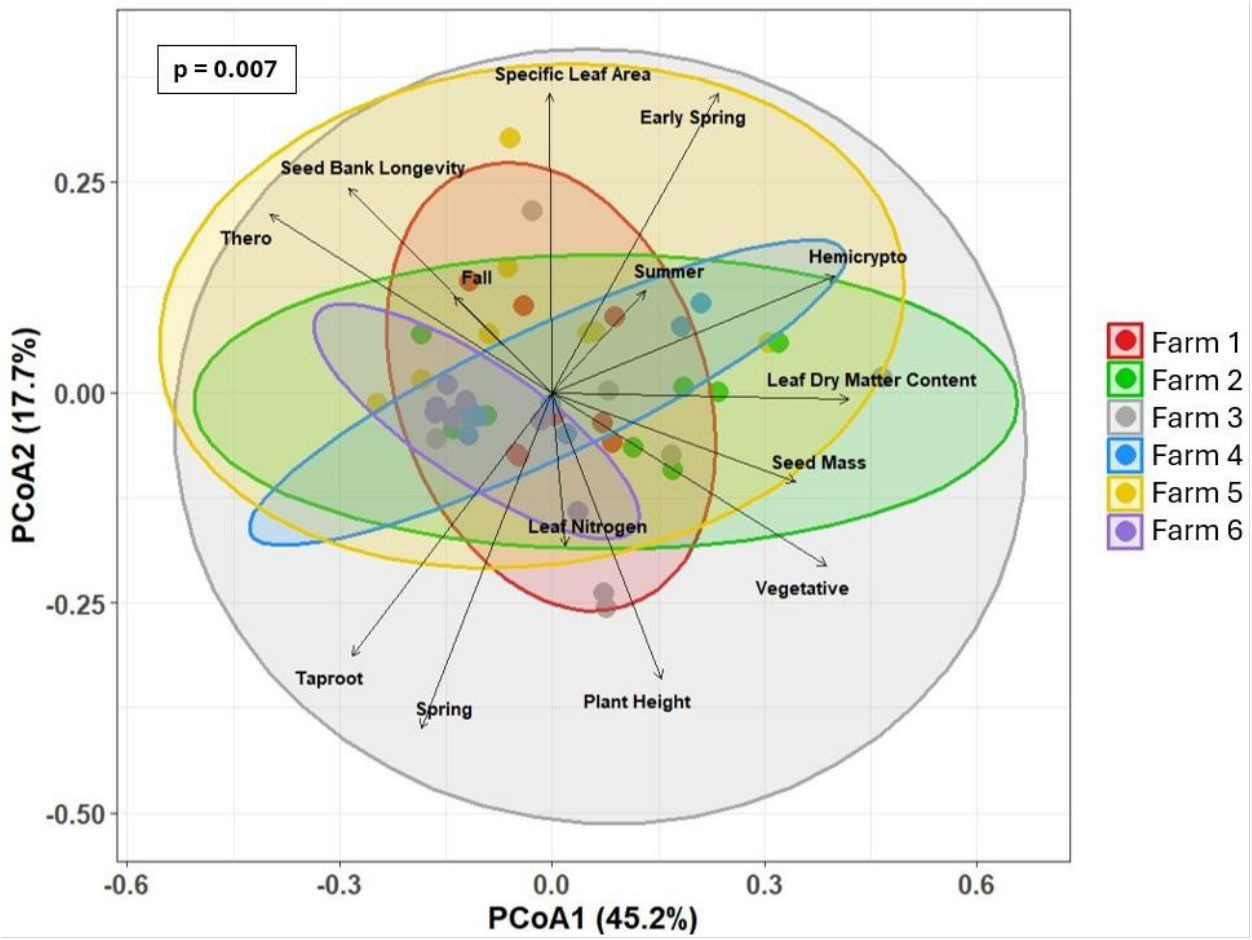


Figure 4: Principal coordinates analysis (PCoA) of biomass-weighted community-weighted mean (CWM) trait values based on Gower distance, showing weed community functional composition across farms. Points represent individual communities sampled on organic vegetable farms, and ellipses indicate 95% confidence intervals for each farm. Arrows represent trait vectors, with direction and length indicating the strength and orientation of each trait's association with ordination space. Weed community functional composition differed significantly among farms (PERMANOVA, $R^2 = 0.21$, $p = 0.007$).

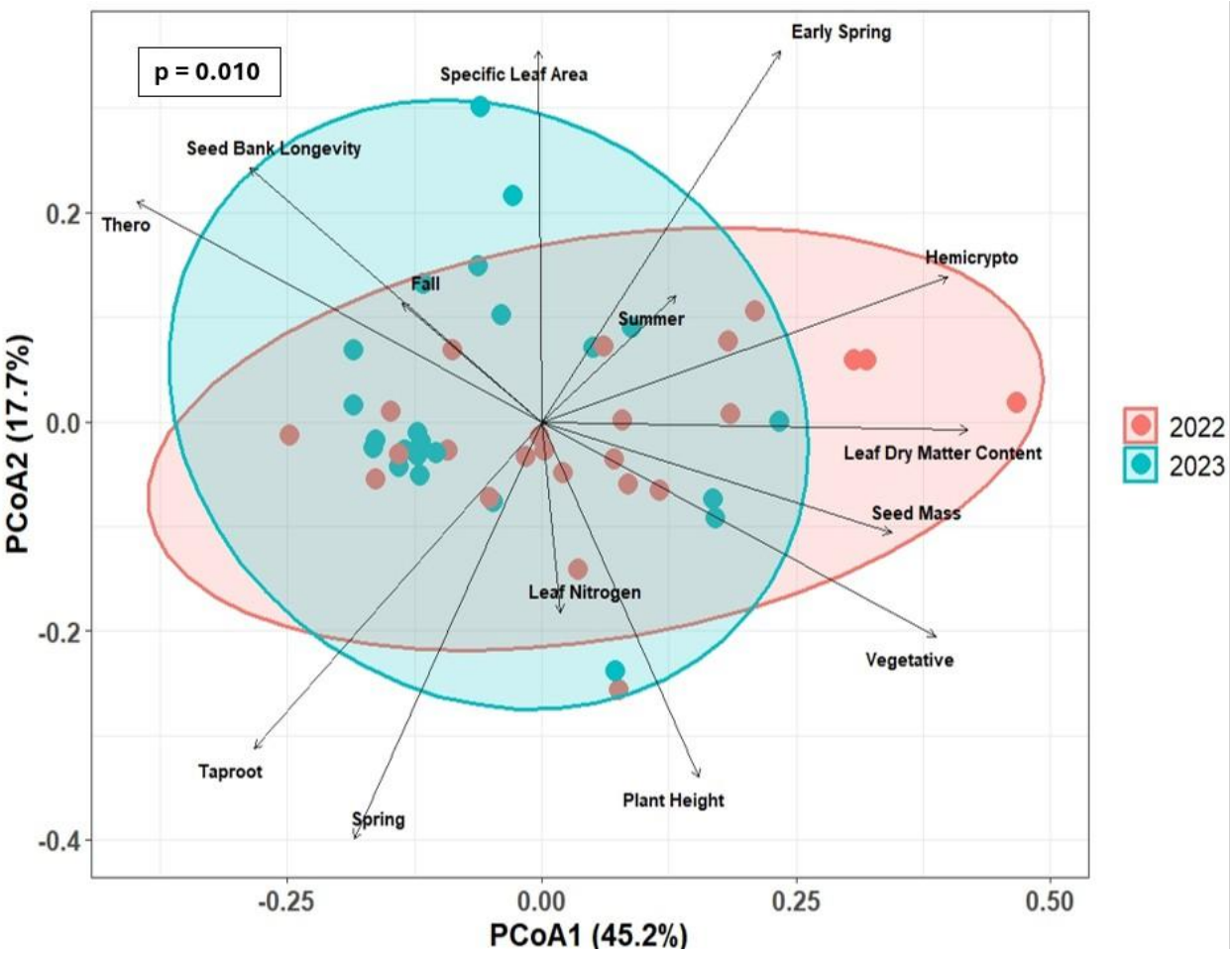


Figure 5: Principal coordinates analysis (PCoA) of biomass-weighted community-weighted mean (CWM) trait values based on Gower distance, showing weed community functional composition across years (2022 and 2023). Points represent individual communities sampled on organic vegetable farms, and ellipses indicate 95% confidence intervals for each year. Arrows represent trait vectors. Functional composition differed significantly between years (PERMANOVA, $R^2 = 0.07$, $p = 0.010$), indicating temporal shifts in trait composition.

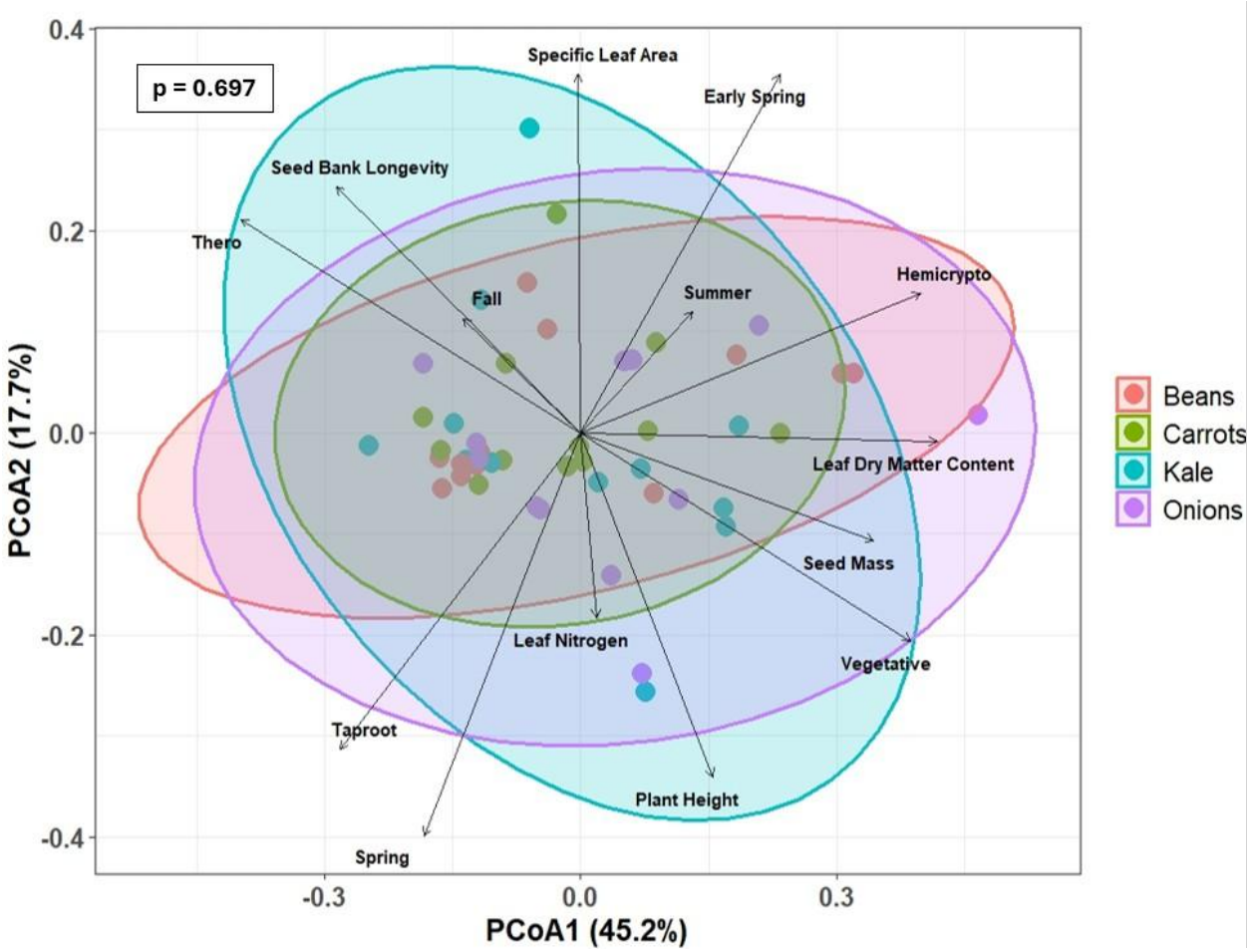


Figure 6: Principal coordinates analysis (PCoA) of biomass-weighted community-weighted mean (CWM) trait values based on Gower distance, showing weed community functional composition across crop types (beans, carrots, kale, and onions). Points represent individual communities sampled on organic vegetable farms, and ellipses indicate 95% confidence intervals for each crop. Arrows represent trait vectors. No significant differences in functional composition were detected among crops (PERMANOVA, $R^2 = 0.04$, $p = 0.697$).

Analysis of individual trait responses further supported the dominant role of farm in structuring weed functional composition (Figure 7). Across traits, there was strong evidence that farm explained variation in several key traits, particularly leaf nitrogen content ($R^2 = 0.550$, $p < 0.001$), plant height ($R^2 = 0.298$, $p = 0.006$), and therophyte life form ($R^2 = 0.263$, $p = 0.016$). There was also evidence that farm influenced leaf dry matter content ($R^2 = 0.237$, $p = 0.029$), while evidence for effects on other traits, including emergence timing and seed mass, was weaker ($p > 0.05$). Year explained less variation overall, although there was evidence of effects on several traits, including vegetative reproduction ($R^2 = 0.127$, $p = 0.007$), hemicryptophyte life form ($R^2 = 0.108$, $p = 0.017$), therophyte life form ($R^2 = 0.090$, $p = 0.022$), and seedbank longevity ($R^2 = 0.093$, $p = 0.032$). There was also weaker evidence for effects on summer emergence ($R^2 = 0.076$, $p = 0.050$), while no evidence of year effects was observed for other traits ($p > 0.10$). In contrast, crop identity explained relatively little variation across traits, with limited evidence of effects on any individual trait ($p > 0.20$), although weak evidence was observed for seedbank longevity ($R^2 = 0.133$, $p = 0.087$).

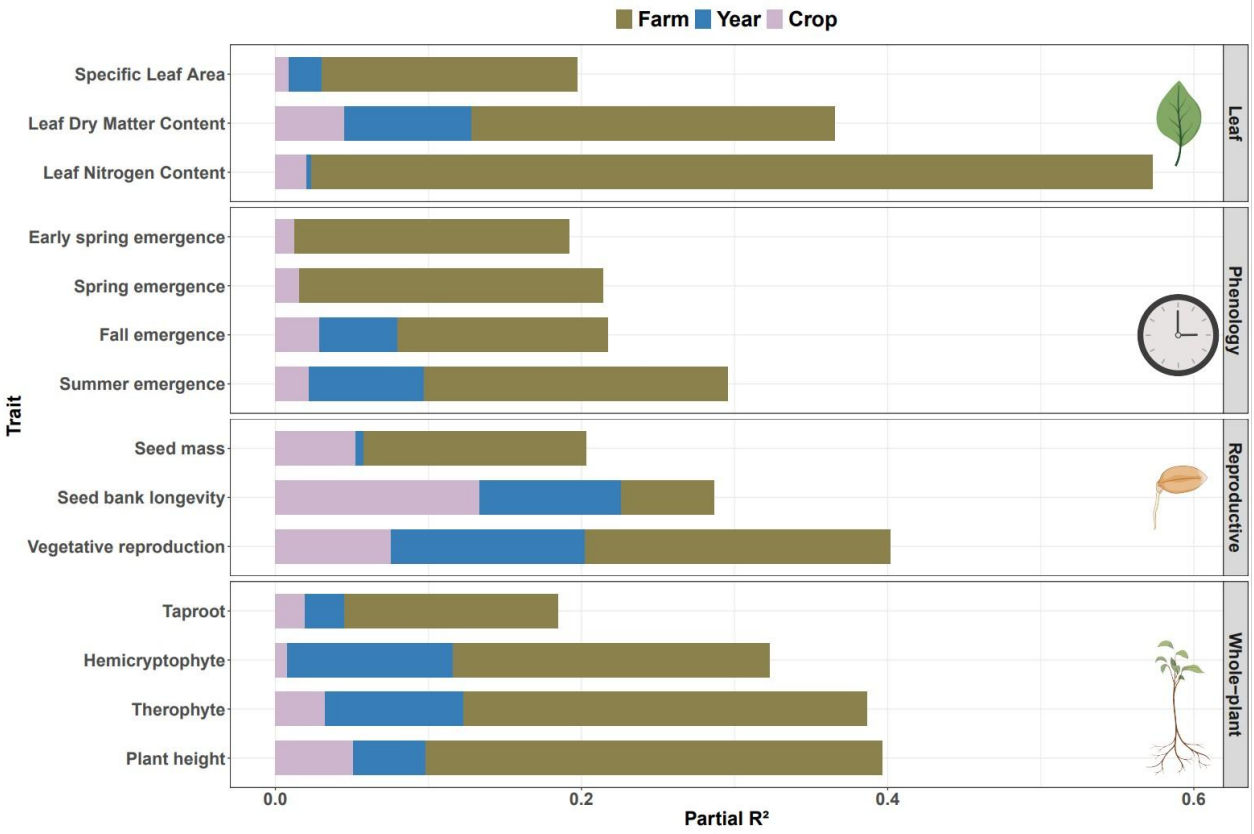


Figure 7: Relative contributions of crop, farm, and year to variation in community-weighted mean (CWM) trait values of weed communities on organic vegetable farms. Bars represent partial R^2 values derived from linear models (trait ~ crop + farm + year), indicating the proportion of variance explained by each factor for individual traits. Traits are grouped by functional category (leaf, phenology, reproductive, and whole-plant traits) to highlight their relative importance in structuring weed communities.

Discussion

Understanding the factors that determine the abundance and diversity of weeds within agroecosystems is a necessary step toward developing ecologically based integrated weed management programs (Booth and Swanton 2002; MacLaren et al. 2020). While on farm research has been conducted to assess weed communities in large-scale cropping systems (Derrouch et al. 2022; Mahaut et al. 2019), to the best of our knowledge, this is the first formal study evaluating weed communities directly on organic small-scale vegetable farms Overall, our

results show that weed community composition in small-scale vegetable organic farms is primarily structured by farm-level filters, with weaker contributions from years. However, contrary to our expectations, crop type did not influence weed community composition. These results suggest that while management practices and site-specific environmental conditions act as dominant drivers of community assembly in small-scale organic vegetable farms, crop-level filtering factors play a limited role in structuring these communities. These results are in agreement with other studies that demonstrate a dominance of regional and environmental factors in shaping weed communities (Cordeau et al. 2017a; Mahaut et al 2019). Similarly, work in cover crop systems has shown that the amount of biomass produced can override the influence of crop identity on weed community filtering (Smith et al. 2015; Buchanan et al. 2016), suggesting that crop biomass may have suppressed differences in weed communities among crop types in our study.

Across all sites and years, low evenness characterized the weed communities, with *Sonchus oleraceus*, *Amaranthus retroflexus*, and *Stellaria media* jointly accounting for more than 45% of total sampled biomass. Such dominance of a few species is common in frequently disturbed agroecosystems that select traits that promote rapid establishment and reproduction under high resource availability (Derrouch et al. 2022; Gaba et al. 2017; Testani et al. 2019). For example, midseason tillage in vegetable systems favors species capable of producing seeds throughout the growing season (Mohler et al. 2018), a characteristic present in the three dominant species identified in our study. In agreement, previous studies show that agricultural weed communities are characterized by a few dominant species alongside many rare, low-density species (Buchanan et al. 2016; Derrouch et al. 2022; Jernigan et al. 2017). These low-

abundance species are frequently associated with dispersal from surrounding landscapes or field edges, contributing to shifting species richness (Aliginer et al. 2020; Petit et al. 2016; Kang et al. 2013). However, these rare species are unlikely to influence weed community functional diversity, as the biomass ratio hypothesis predicts that the traits of dominant species primarily determine ecosystem processes and functioning (Garnier and Navas 2012; Grime 1998).

Our functional trait-based analysis indicated a range of communities across farms from those dominated by annual, seed-based, disturbance adapted strategies, characterized by spring emergence and longer seedbank persistence, to those characterized by persistence strategies, including vegetative reproduction, hemicryptophyte life forms, higher leaf dry matter content, and greater seed mass. These results highlight the importance that farm identity has as a strong filter shaping trait selection and weed communities. Differences among farms likely reflect variation in the type, timing, and consistency of management practices (Booth and Swanton 2002), including soil fertility (Little et al. 2021), nutrient management (Cordeau et al. 2021), weed management practices (Brown and Gallandt 2019), and historical land use (Leeson et al. 2000). In addition, variation in resource availability appears to contribute to farm-level filtering. Leaf nitrogen content and specific leaf area are key components of the leaf economics spectrum, and differences among farms indicate shifts in community-level resource-use strategies, reflecting differences between fast-growing, acquisitive species versus those with more conservative growth strategies (Garnier and Navas 2012). The system-level nature of our study precludes us to evaluate specific mechanisms driving these associations, but research is warranted on the impact of environmental, biological, and management variables on trait selection.

The observed shifts in functional traits among farms have important implications for how weed communities interact with crops and respond to management. Communities dominated by short-lived, disturbance-adapted species with rapid growth and early reproduction are likely to exert strong, early-season competitive pressure, but may also be more responsive to early-season tillage (Cordeau et al. 2017a). In contrast, communities with greater representation of persistent strategies, such as vegetative reproduction and longer-lived life forms, are less responsive to short-term management interventions, contributing to longer-term persistence within fields (Testani et al. 2019), strategies that have been cited by organic farmers as one of their largest challenges (McKenzie et al. 2018).

Year also influenced weed functional trait composition, although less strongly than farm. Across the two years, communities shifted along a trait gradient from species associated with vegetative reproduction and hemicryptophytic life forms toward those characterized by therophyte life histories and greater reliance on persistent seedbanks. These shifts likely reflect interannual variation in environmental conditions, including temperature and precipitation, factors that can influence weed germination, emergence timing, and survival following disturbance, therefore shaping which life-history strategies are most successful (Marschner et al. 2024; Travlos et al. 2020). Our results agree with previous work demonstrating variation in weed community composition across years (Ciaccia et al. 2020; Edesi et al. 2012). Additionally, interannual effects are often compounded by interactions between weather and management. For example, unfavorable weather conditions can change tillage timing, resulting in incomplete suppression and subsequent pulses of seed production that influence community composition (Smith 2006; Cordeau et al. 2017a; Cordeau et al. 2017b; Cordeau et al. 2017c). These

management shifts can alter the relative abundance of functional strategies over time, reinforcing the dominance of certain species or traits across years (Buhler et al. 1997; Cavers 1995; Mohler et al. 2018).

Crop identity influences weed communities through differences in phenology, canopy architecture, and management timing (Fried et al. 2008; Mohler et al. 2018). As such, we expected a strong association between crop type and weed functional traits. In contrast to our expectations and in agreement with previous studies (Allen et al. 2024; Leoni et al. 2026; Menalled et al. 2023; Pyšek et al. 2005), crop identity had little effect on weed functional composition. Our results indicate farm-level management and environmental conditions may have overridden crop-specific community assembly processes. Additionally, the timing of sampling may have affected the relative abundance of weed species (Hyvönen et al. 2003; Lososová et al. 2004) and the extent to which crops influenced weed communities, warranting the need of within-year assessment of shifts in functional traits. For example, crop competitive effects and therefore, selection pressures, may be more pronounced earlier in the growing season when initial competitive asymmetries could impact weed-crop competition (Mcdonald et al. 2010; Savić et al. 2025; Weaver 1984). The logistic of sampling across all crops and time precluded us from evaluating within-season trends in trait selection, a topic that could deserve analysis.

Functional diversity metrics showed a more limited response to year, farm, and crop than functional composition. Functional richness varied among farms, while Rao's quadratic entropy varied between years, while the other indices showed little evidence of differences. These contrasting responses indicate that farm and year level filtering influenced different aspects of

overall community structure. Specifically, farms likely altered the range of trait values present, whereas interannual variation primarily shifted the relative abundance of species already present. Functional richness represents the range of trait values within a community and is therefore sensitive to the presence of species with more extreme trait values, even if they are rare (Mason et al. 2005; Cornwall et al. 2006; Villéger et al. 2008). In contrast, metrics such as functional dispersion and evenness are weighted by species relative abundance and describe the distribution of biomass within that trait space (Laliberté and Legendre 2010; Villéger et al. 2008). Rao' quadratic entropy integrates both species' relative abundances and their trait dissimilarities (Laliberté and Legendre 2010), making it sensitive to shifts in the relative dominance of functionally distinct species, even when the overall range and distribution of traits remain similar. Similar variation in response to functional diversity metrics has been observed in other agroecosystems. Hernández Plaza et al. (2015) showed that functional richness was strongly influenced by the presence of less abundant species with extreme trait values, whereas abundance-weighted metrics such as functional dispersion reflected the distribution of dominant species within the community.

Shifting weed communities towards less competitive ones is a central tenet of ecological management of agricultural weeds (Liebman et al. 2001). Our results suggest that such efforts in small-scale diversified organic vegetable systems may be more effective when tactics are implemented at the farm scale rather than the crop scale. At the same time, the strong dominance of a few species indicates that management should pay particular attention to the strategies associated with those dominant taxa, since they are likely to drive both crop interference (Hernández Plaza et al. 2015; Storkey and Neve 2018) and broader community structure and

function (Garnier and Navas 2012). This reinforces the importance of viewing weed communities through a community assembly framework (MacLaren et al. 2020) where multiple interacting filters determine which species and ecological strategies persist. By highlighting the central role of management as an ecological filter, our findings provide a foundation for ecological weed management recommendations within small-scale organic vegetable systems in Montana and surrounding areas.

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Supplemental Table 1: Site characteristics, management information, and soil properties by farm, crop, and depth across all sites and years. Soil samples were collected within crop rows at two depths (0-6 cm and 6-24 cm), and values represent samples combined from three cores per field. Soil properties include pH, organic matter (OM), nitrate, and extractable phosphorus (P), potassium (K), and zinc (Zn). Mean temperature and total precipitation were calculated for each region and year from May 1 through August 1. Farm-level summaries are presented in Table 1.

Farm	Year	Region	Avg Temp (C°)	Total precip (mm)	Farm Size	Years Farmed	Crop	Depth 1	Depth 2	pH Depth 1	pH Depth 2	OM	Nitrate Depth 1	Nitarte Depth 2	P ppm	K ppm	Z ppm
Farm 1	2022	Gallatin	15.2	184	5-9.9 ac	5-9 years	Bean	0-6	6-24	7.7	7.6	4.6	15.0	4.5	25	167	1.38
							Carrot	0-6	6-24	7.1	7.2	5.6	11.0	8.0	37	153	2.55
							Kale	0-6	6-24	7.2	7.0	5.1	9.0	7.5	18	191	1.72
							Onion	0-6	6-24	7.2	7.1	5.2	10.5	11.0	21	157	3.92
Farm 2	2022	Gallatin	15.2	184	> 1 ac	1-4 years	Bean	0-6	6-24	6.9	7.3	6.1	29.5	14.0	14	227	2.02
							Carrot	0-6	6-24	7.1	7.4	6.6	42.5	40.5	37	398	1.83
							Kale	0-6	6-24	7.5	7.7	6.1	31.0	13.5	13	183	1.13
							Onion	0-6	6-24	7.6	7.8	7.1	26.0	12.0	25	260	1.53
Farm 3	2022	Gallatin	15.2	184	1-4.9 ac	5-9 years	Bean	0-6	6-24	7.3	7.4	3.9	24.0	15.0	26	493	1.68
							Carrot	0-6	6-24	7.2	7.3	4.5	19.0	9.0	41	746	2.22
							Kale	0-6	6-24	7.2	7.1	3.0	4.5	8.0	23	362	1.22
							Onion	0-6	6-24	7.1	6.6	8.4	42.5	10.5	57	783	2.55
Farm 4	2022	Bitterroot	15.2	309	5-9.9 ac	20+ years	Bean	0-6	6-24	8.0	7.9	5.1	19.5	4.5	7	186	0.97
							Carrot	0-6	6-24	8.2	8.0	6.3	15.5	9.5	6	233	1.06
							Kale	0-6	6-24	8.3	8.3	5.7	25.5	2.0	4	361	0.74
							Onion	0-6	6-24	8.3	8.2	5.8	21.5	4.5	6	333	0.92
Farm 5	2022	Gallatin	15.2	184	5-9.9 ac	10-19 years	Bean	0-6	6-24	7.7	8.2	3.3	64.0	18.5	24	423	2.77
							Carrot	0-6	6-24	7.5	8.0	3.8	7.5	7.0	19	220	2.72
							Kale	0-6	6-24	7.9	8.3	4.1	34.5	9.0	14	258	2.43
							Onion	0-6	6-24	7.4	8.2	2.8	9.0	6.5	22	228	5.08
Farm 6	2022	Bitterroot	15.2	309	5-9.9 ac	10-19 years	Bean	0-6	6-24	7.9	8.3	2.8	10.5	8.0	86	692	2.8
							Carrot	0-6	6-24	7.9	8.1	3.2	9.5	7.5	98	729	4.07
							Kale	0-6	6-24	7.8	8.0	2.7	11.5	6.5	79	623	1.52
							Onion	0-6	6-24	7.8	8.0	2.7	10.5	4.5	86	641	3.25
Farm 1	2023	Gallatin	15.9	173	5-9.9 ac	5-9 years	Bean	0-6	6-24	6.8	6.9	6.4	22	105	32	196	4.04
							Carrot	0-6	6-24	6.8	6.8	6.4	16	36	31	187	2.39
							Kale	0-6	6-24	6.6	6.7	6.6	28	75	32	232	2.85
							Onion	0-6	6-24	7.3	7.4	7	15	36	44	186	3.81
Farm 2	2023	Gallatin	15.9	173	> 1 ac	1-4 years	Bean	0-6	6-24	7.6	7.5	4.4	12	60	14	197	0.55
							Carrot	0-6	6-24	7.7	7.8	5.8	42	120	20	244	0.84
							Kale	0-6	6-24	7.6	7.8	5.7	43	75	19	211	1.3
							Onion	0-6	6-24	7.1	7.2	6.7	30	54	28	377	1.39
Farm 3	2023	Gallatin	15.9	173	1-4.9 ac	5-9 years	Bean	0-6	6-24	7.3	7.3	4.8	51	150	38	1052	1.58
							Carrot	0-6	6-24	7.8	7.9	6.1	28	78	34	464	1.74
							Kale	0-6	6-24	7.2	7.2	9.4	43	48	50	755	3.17
							Onion	0-6	6-24	7.3	7.2	4.3	21	48	57	598	2.2
Farm 4	2023	Bitterroot	18	96	5-9.9 ac	20+ years	Bean	0-6	6-24	7.8	8.1	7	68	144	95	645	3.98
							Carrot	0-6	6-24	8.2	8.1	7.4	104	780	65	2357	1.62
							Kale	0-6	6-24	8	8	6.4	39	87	72	704	2.49
							Onion	0-6	6-24	8	8.4	5.4	28	129	10	755	1.72
Farm 5	2023	Gallatin	15.9	173	5-9.9 ac	10-19 years	Bean	0-6	6-24	7.2	6.9	5.4	55	102	32	369	11.5
							Carrot	0-6	6-24	7.3	8	4.9	99	198	27	362	4.41
							Kale	0-6	6-24	6.8	8	5.2	40	18	15	172	14
							Onion	0-6	6-24	6.6	7.8	4.9	32	39	21	230	6.61
Farm 6	2023	Bitterroot	18	96	5-9.9 ac	10-19 years	Bean	0-6	6-24	7.8	7.6	4	16	30	127	926	7.08
							Carrot	0-6	6-24	7.9	8	3.9	13	30	84	741	2.41
							Kale	0-6	6-24	7.8	8.4	3.9	21	27	90	832	2.08
							Onion	0-6	6-24	7.7	7.9	3.9	24	42	103	783	2.38

Supplemental Table 2: Trait values for all weed species are included in the functional trait analyses. Traits were compiled from TRY, LEDA Traitbase, and additional published sources. Continuous traits were standardized prior to analysis, and categorical traits were converted to binary variables. These data were used to calculate community-weighted means (CWM) for each site-year-crop combination.

Species	Seedbank Longevity	Sources	Primary Emergence	Source	Specific Leaf Area	Sources
Acer negundo	1	Bonner 2008	Spring	The Ohio State University	22.79985765	TRY Database
Amaranthus retroflexus	3	Colorado State University	Spring	Menelled et al. 2022	15.82666383	TRY Database
Anethum graveolens	1	University of Wisconsin Extension	Spring	Utah State University	18.842	TRY Database
Anthemis cotula	2	Mohler et al. 2022	Spring	Lyons et al 2022	21.09233135	TRY Database
Avena fatua	2	Mohler et al. 2022	Early Spring	Becki et al. 2012	17.41250164	TRY Database
Berteroa incana	2	Montana Field Guide	Early Spring	Montana Field Guide	19.46	TRY Database
Capsella bursa-pastoris	3	Mohler et al. 2021	Fall	Mohler et al. 2022	31.19857445	TRY Database
Calystegia sepium	3	Mohler et al. 2022	Spring	Mohler et al. 2022	37.81493446	TRY Database
Centaurea stoebe	3	Davis et al. 2017	Early Spring	Duncan et al 2017	25.852	TRY Database
Cerastium fontanum	2	Bond and Davies 2007	Early Spring	Pudue University	26.58363382	TRY Database
Chenopodium album	3	Mohler et al. 2022	Spring	Menelled et al. 2022	27.46337853	TRY Database
Cirsium arvense	2	Jacobs et al. 2006	Spring	Mohler et al. 2022	17.45397538	TRY Database
Convolvulus arvensis	3	Fire Effects Information System (FEIS) Forest Service	Spring	Mohler et al. 2022	25.21830127	TRY Database
Echinochloa crus-galli	2	Mohler et al. 2022	Spring	Menelled et al. 2022	31.50676014	TRY Database
Elymus repens	2	Mohler et al. 2022	Early Spring	University of Minnesota	24.58270121	TRY Database
Erodium cicutarium	2	CABI https://doi.org/10.1079/cabicompendium.2184	Early Spring	Menelled et al. 2022	25.84736729	TRY Database
Fallopia convolvulus	3	Mohler et al. 2021	Spring	Menelled et al. 2022	21.883804	TRY Database
Salsola tragus	1	Mohler et al. 2022	Summer	Mohler et al. 2022	14.46483182	TRY Database
Lactuca serriola	2	Mohler et al. 2023	Summer	Menelled et al. 2022	19.33902404	TRY Database
Lamium amplexicaule	3	Mohler et al. 2024	Spring	Mohler et al. 2022	21.67733333	TRY Database
Malva neglecta	3	Pudue University	Spring	Purdue University	24.67864078	TRY Database
Medicago lupulina	3	Lewis 2006	Early Spring	Menelled et al. 2022	32.01000755	TRY Database
Medicago sativa	3	Bass et al. 1998	Early Spring	Nebraska Extension	21.92874583	TRY Database
Mentha spicata	2	ALASKA NON-NATIVE PLANT INVASIVENESS RANKING FORM	Spring	North Carolina University	22.5	TRY Database
Nepeta cataria	2	The Ohio State University	Early Spring	University of Wisconsin Extension	28.33682896	TRY Database
Panicum capillare	2	Mohler et al. 2021	Summer	Mohler et al. 2022	27.35044754	TRY Database
Persicaria maculosa	3	Mohler et al. 2022	Early Spring	Mohler et al. 2023	37.68951118	TRY Database
Plantago major	3	Mohler et al. 2023	Spring	Mohler et al. 2024	20.58224827	TRY Database
Poa pratensis	2	WSARE	Summer	Mohler et al. 2022	22.67285548	TRY Database
Polygonum aviculare	3	Conn et al. 2006	Spring	Menelled et al. 2022	24.48179992	TRY Database
Portulaca oleracea	3	Mohler et al. 2022	Spring	Menelled et al. 2022	17.47752773	TRY Database
Setaria viridis	3	Mohler et al. 2022	Summer	Menelled et al. 2022	26.96617218	TRY Database
Silene latifolia	3	Lewis 1973	Spring	The Ohio State University	19.58624969	TRY Database
Sisymbrium altissimum	2	The University of Arizona	Fall	Montana State University	20.55333333	TRY Database
Solanum dulcmara	3	WSARE	Summer	Menelled et al. 2022	36.89748	TRY Database
Sonchus oleraceus	2	Mohler et al. 2022	Spring	Menelled et al. 2022	39.65001051	TRY Database
Spergula arvensis	3	Chippendale and Milton 1934	Spring	Alaska Center for Conservartion Science	18.30268669	TRY Database
Stellaria media	3	Mohler et al. 2022	Early Spring	Menelled et al. 2022	64.82416751	TRY Database
Taraxicum officinale	2	Mohler et al. 2022	Summer	Menelled et al. 2022	37.3	LEDA Database
Thlaspi arvense	3	Mohler et al. 2022	Spring	Mohler et al. 2022	25.39939901	TRY Database
Trifolium hybridum	3	Lewis 1973	Early Spring	Menelled et al. 2022	25.58519184	TRY Database
Trifolium pratense	3	Lewis 1973	Early Spring	Menelled et al. 2022	24.31918128	TRY Database
Trifolium repens	3	Lewis 1973	Early Spring	Menelled et al. 2022	26.7594201	TRY Database
Verbascum thapsus	3	US Forest Service	Summer	Menelled et al. 2022	15.79535676	TRY Database

Species	Leaf Dry Matter Content	Sources	Leaf Nitrogen Content	Sources	Plant height	Sources
Acer negundo	0.291204401	TRY Database	1.399410116	TRY Database	11.5	LEDA Database
Amaranthus retroflexus	0.204327778	TRY Database	1.435581749	TRY Database	0.451666667	LEDA Database
Anethum graveolens	0.166723	TRY Database	1.396	Brinsi et al. 2024	0.61	LEDA Database
Anthemis cotula	0.167018406	TRY Database	1.904588052	TRY Database	0.285	LEDA Database
Avena fatua	0.237946743	TRY Database	0.826111959	TRY Database	0.75	LEDA Database
Berteroa incana	0.234574036	TRY Database	1.92	Snell-Rood et al. 2014	0.325	LEDA Database
Capsella bursa-pastoris	0.154880851	TRY Database	1.269953147	TRY Database	0.126666667	LEDA Database
Calystegia sepium	0.166342929	TRY Database	0.869282111	TRY Database	1.2875	LEDA Database
Centaurea stoebe	0.177863529	TRY Database	1.137653635	LEDA Database	0.475	LEDA Database
Cerastium fontanum	0.211066994	TRY Database	0.826045797	TRY Database	0.11	LEDA Database
Chenopodium album	0.156538518	TRY Database	2.074858488	TRY Database	0.483333333	LEDA Database
Cirsium arvense	0.17621954	TRY Database	1.454676156	TRY Database	0.8625	LEDA Database
Convolvulus arvensis	0.175569703	TRY Database	1.623202102	TRY Database	0.2626	LEDA Database
Echinochloa crus-galli	0.221209125	TRY Database	0.668441983	TRY Database	0.575	LEDA Database
Elymus repens	0.341462996	TRY Database	1.340749062	TRY Database	0.75	LEDA Database
Erodium cicutarium	0.19840172	TRY Database	0.942663285	TRY Database	0.6	LEDA Database
Fallopia convolvulus	0.210037569	TRY Database	0.314066919	TRY Database	0.6875	LEDA Database
Salsola tragus	0.113691087	TRY Database	1.64342703	TRY Database	0.5125	LEDA Database
Lactuca serriola	0.188274396	TRY Database	1.638139682	TRY Database	0.675	LEDA Database
Lamium amplexicaule	0.145066642	TRY Database	1.36	Wang et al 2023	0.133333333	LEDA Database
Malva neglecta	0.253236909	TRY Database	1.09	Ozer and Askoy 2019	0.283333333	LEDA Database
Medicago lupulina	0.244577015	TRY Database	1.226761265	TRY Database	0.25	LEDA Database
Medicago sativa	0.266679721	TRY Database	2.199863835	TRY Database	0.35	LEDA Database
Mentha spicata	0.2344	TRY Database	1.56	Cano-Gallego et al. 2023	0.475	LEDA Database
Nepeta cataria	0.269088829	TRY Database	0.7901285	TRY Database	0.566666667	LEDA Database
Panicum capillare	0.285285176	TRY Database	0.847334834	TRY Database	0.8	LEDA Database
Persicaria maculosa	0.139022346	TRY Database	0.861512261	TRY Database	0.383333333	LEDA Database
Plantago major	0.179673132	TRY Database	1.397798015	TRY Database	0.37	LEDA Database
Poa pratensis	0.335147698	TRY Database	0.963335469	TRY Database	0.3	LEDA Database
Polygonum aviculare	0.23116741	TRY Database	1.364704229	TRY Database	1.1375	LEDA Database
Portulaca oleracea	0.076794227	TRY Database	0.331484996	TRY Database	0.166666667	LEDA Database
Setaria viridis	0.275550187	TRY Database	0.761308741	TRY Database	0.5125	LEDA Database
Silene latifolia	0.164839541	TRY Database	1.197105022	LEDA Database	0.475	LEDA Database
Sisymbrium altissimum	0.193882273	TRY Database	1.972781737	LEDA Database	0.54625	LEDA Database
Solanum dulcmara	0.184277	TRY Database	1.069165	TRY Database	0.866666667	LEDA Database
Sonchus oleraceus	0.133200655	TRY Database	1.516530806	TRY Database	1.075	LEDA Database
Spergula arvensis	0.122909869	TRY Database	2.381320996	TRY Database	0.2	LEDA Database
Stellaria media	0.13063557	TRY Database	0.805523098	TRY Database	0.166666667	LEDA Database
Taraxicum officinale	0.1487	LEDA Database	1.03	LEDA Database	0.3	LEDA Database
Thlaspi arvense	0.13966792	TRY Database	1.63418	TRY Database	0.35	LEDA Database
Trifolium hybridum	0.226981766	TRY Database	1.597103724	TRY Database	0.35	LEDA Database
Trifolium pratense	0.271858298	TRY Database	1.612391095	TRY Database	0.283333333	LEDA Database
Trifolium repens	0.234830826	TRY Database	1.364178402	TRY Database	0.35	LEDA Database
Verbascum thapsus	0.230388684	TRY Database	1.022426271	TRY Database	0.783333333	LEDA Database

Species	Seed dry mass	Sources	Raunkiaer Life Form	Sources	Plant Root Type	Sources
Acer negundo	37.2984572	TRY Database	phanerophyte	TRY Database	FIB	USDA PLANTS Database
Amaranthus retroflexus	0.444265333	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Anethum graveolens	1.716564706	TRY Database	therophyte	TRY Database	TAP	University of Wisconsin -Madison Extension
Anthemis cotula	0.39305	TRY Database	therophyte	TRY Database	TAP	University of Wisconsin-Madison Extension
Avena fatua	15.89058213	TRY Database	therophyte	TRY Database	FIB	USDA PLANTS Database
Berteroa incana	0.558983333	TRY Database	hemicryptophyte	TRY Database	TAP	USDA PLANTS Databse
Capsella bursa-pastoris	0.130735833	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Calystegia sepium	28.19270666	TRY Database	geophyte	TRY Database	TAP	Mohler et al. 2022
Centaurea stoebe	1.885910882	TRY Database	hemicryptophyte	TRY Database	TAP	University of Califfornia IPM
Cerastium fontanum	0.134363105	TRY Database	hemicryptophyte	TRY Database	FIB	Mohler et al. 2022
Chenopodium album	0.705614654	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Cirsium arvense	1.337204301	TRY Database	geophyte	TRY Database	TAP	Fire Effects Information System (FEIS) Forest Service
Convolvulus arvensis	12.69464925	TRY Database	geophyte	TRY Database	TAP	Fire Effects Information System (FEIS) Forest Service
Echinochloa crus-galli	1.880589362	TRY Database	therophyte	TRY Database	FIB	Mohler et al. 2022
Elymus repens	2.772875938	TRY Database	hemicryptophyte	TRY Database	FIB	Mohler et al. 2022
Erodium cicutarium	1.9178991	TRY Database	therophyte	TRY Database	TAP	Colorado Department of Ariculture
Fallopia convolvulus	5.257035088	TRY Database	therophyte	TRY Database	FIB	Mohler et al. 2022
Salsola tragus	1.74611	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Lactuca serriola	0.460535338	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Lamium amplexicaule	0.572800992	TRY Database	therophyte	TRY Database	TAP	University of Wisconsin-Madison Extension
Malva neglecta	2.309525769	TRY Database	therophyte	TRY Database	TAP	Penn State
Medicago lupulina	1.573118439	TRY Database	hemicryptophyte	TRY Database	TAP	North Carolina State Extension
Medicago sativa	2.245668655	TRY Database	hemicryptophyte	TRY Database	TAP	USDA PLANTS Database
Mentha spicata	0.04	TRY Database	hemicryptophyte	TRY Database	FIB	Illinois Wildflowers
Nepeta cataria	0.546304444	TRY Database	hemicryptophyte	TRY Database	TAP	The Ohio State University
Panicum capillare	0.2775025	TRY Database	therophyte	TRY Database	FIB	Mohler et al. 2022
Persicaria maculosa	2.030390679	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Plantago major	0.217217823	TRY Database	hemicryptophyte	TRY Database	FIB	Purdue University
Poa pratensis	0.278111171	TRY Database	hemicryptophyte	TRY Database	FIB	Mohler et al. 2022
Polygonum aviculare	1.561373627	TRY Database	therophyte	TRY Database	TAP	Penn State
Portulaca oleracea	0.179529392	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Setaria viridis	1.27981844	TRY Database	therophyte	TRY Database	FIB	Mohler et al. 2022
Silene latifolia	1.134582126	TRY Database	hemicryptophyte	TRY Database	TAP	The Ohio State University
Sisymbrium altissimum	0.120605	TRY Database	therophyte	TRY Database	TAP	The University of Arizona
Solanum dulcmara	22.69763703	TRY Database	therophyte	TRY Database	FIB	PLANTS Database
Sonchus oleraceus	0.270890169	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Spergula arvensis	0.423741176	TRY Database	therophyte	TRY Database	TAP	Penn State
Stellaria media	0.36546122	TRY Database	therophyte	TRY Database	FIB	North Carolina State Extension
Taraxicum officinale	0.5316	LEDA Database	therophyte	LEDA Database	TAP	LEDA Database
Thlaspi arvense	1.089132836	TRY Database	therophyte	TRY Database	TAP	Mohler et al. 2022
Trifolium hybridum	0.834666104	TRY Database	hemicryptophyte	TRY Database	TAP	Illiois Wildfowers
Trifolium pratense	1.476490715	TRY Database	hemicryptophyte	TRY Database	TAP	USDA Plant Guide
Trifolium repens	0.620210966	TRY Database	hemicryptophyte	TRY Database	TAP	USDA Plant Guide
Verbascum thapsus	0.149826016	TRY Database	hemicryptophyte	TRY Database	TAP	Mohler et al. 2022

Supplemental Table 3: Weed species observed across all crops, farms, and years, ranked by relative biomass (%). Relative biomass was calculated as the proportion of total aboveground weed biomass contributed by each species across all sampled plots.

Species	Relative biomass (%)
Sonchus oleraceus	18.8%
Amaranthus retroflexus	15.5%
Stellaria media	11.0%
Cirsium arvense	7.7%
Elymus repens	6.5%
Chenopodium album	5.5%
Lamium amplexicaule	4.9%
Portulaca oleracea	4.5%
Taraxicum officinale	2.5%
Persicaria maculosa	2.5%
Sisymbium altissimum	2.3%
Capsella bursapastoris	2.2%
Silene latifolia	2.1%
Malva neglecta	1.7%
Thlaspi arvense	1.3%
Setaria virdis	1.3%
Polygonum aviculare	1.2%
Trifolium repens	1.1%
Poa pratensis	1.0%
Convolvulus arvensis	1.0%
Trifolium hybridium	0.6%
Medicago lupulina	0.6%
Echinochloa crus-galli	0.6%
Plantago major	0.4%
Erodium cicutarium	0.4%
Fallopia convulvulus	0.3%
Lactuca serriola	0.2%
Calystegia sepium	0.2%
Solanum dulcmara	0.2%
Verbascum thapsus	0.1%
Panicum capillare	0.1%
Salsola tragus	0.1%
Cerastrium fontanum	0.1%
Nepeta cataria	0.1%
Acer negundo	0.0%
Medicago sativa	0.0%
Spergula arvensis	0.0%
Berteroa incana	0.0%
Trifolium pratense	0.0%
Bromus tectorum	0.0%
Avena fatua	0.0%
Anthemis cotula	0.0%
Centaurea stoebe	0.0%
Anethum graveolens	0.0%
Mentha spicata	0.0%

CHAPTER FIVE

TEACHING ECOLOGICAL WEED MANAGEMENT: A LABORATORY EXERCISE ON WEED COMMUNITY ASSEMBLY

Contribution of Authors and Co-Authors

Manuscript in Chapter 5

Author: Emma Kubinski

Contributions: Assisted in study conception and design, implemented activity in the classroom, collected data, performed statistical
analysis, and wrote initial manuscript

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Contributions: Assisted in study conception and design, implemented activity in the classroom, collected data, and edited manuscript

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Manuscript Information

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Abstract

As the field of weed science increasingly emphasizes the use of ecologically based weed management, it is essential to prepare future weed scientists and land managers to apply ecological principles to weed management. Although teaching activities have been developed to explain foundational weed ecology and weed biology concepts, many focus on individual species or crop-weed interactions and therefore do not address the multispecies interactions that occur in agroecosystems. To help students examine the complexity of managing weed communities within agricultural systems, we developed the *Weed Communities and Management* laboratory exercise that uses experiential learning to teach the foundational concept of community assembly to weed science students. The exercise was implemented at Cornell University and Montana State University during the Fall 2023 and 2024 semesters with more than 100 undergraduate and graduate students. Pots were seeded with identical weed communities and subjected to management treatments representing organic vegetable production, conventional small grain production, and unmanaged systems. Students quantified weed abundance and diversity and interpreted community shifts using ecological theory through a manuscript style scientific writing assignment. Across universities and years, simulated management systems produced distinct weed communities, with conventional systems consistently supporting lower weed abundance and reduced species diversity relative to organic and unmanaged systems. Student survey responses indicated that the exercise improved understanding of ecological weed management concepts, weed community dynamics, and scientific writing. By connecting management practices to weed community assembly and requiring students to interpret these

patterns using ecological theory, this laboratory exercise provides a framework for teaching ecological weed management and promoting systems level thinking in weed science education.

Introduction

The need to prepare future scientists and land managers to study and manage weeds in ecologically sound and sustainable ways has become increasingly urgent as conventional practices face mounting environmental, social, and economic challenges. For decades, herbicides have served as the dominant tool for weed control. However, the rapid rise of herbicide-resistant weed populations, the lack of new herbicide modes of action, and growing concerns about environmental and human health impacts underscore the limitations of herbicide-centered strategies (Merfield 2020). In response, integrated weed management (IWM), or the use of a combination of chemical, biological, cultural, mechanical, and preventative tools, has been promoted as a more resilient approach to minimize the spread and impact of weeds (Liebman and Gallandt 1997; Harker and O'Donovan 2017). However, to successfully implement IWM tactics, management decisions must be made at the agroecosystem level (Mortensen et al. 2002) and grounded in ecological principles (MacLaren et al. 2020). Building on this foundation, ecological principles can be used to manipulate interactions among crops, weeds, and agroecosystem processes to reduce weed pressure and enhance crop competitiveness (Liebman et al. 2001; Mohler et al. 2021).

A cornerstone of ecological weed management is understanding and manipulating shifts in weed communities and balancing their negative and positive functions, rather than pursuing blanket weed removal (Esposito et al. 2023; MacLaren et al. 2020; Storkey and Neve 2018). Shifting the paradigm of weed science requires new approaches to train the next generation of

professionals on the processes driving weed community assembly; i.e., how dispersal, abiotic, and biotic filters determine which plant species can exist at a given time and place (Keddy 1992; Booth and Swanton 2002). In this context, weed science students should understand how management decisions function as a dominant filter that shapes weed community structure (Ryan et al. 2010). Therefore, connecting management practices to their impact on weed communities is critical.

Students are usually exposed to the concept of weed community assembly through lectures, making it challenging for them to connect these ideas to real-world management scenarios (Lewinsohn et al. 2015). As a result, students may struggle to apply ecological principles and system-level thinking when interpreting weed management challenges. Finding better ways to explain these hard-to-grasp concepts is essential to improve student learning of ecological principles driving agricultural weed community dynamics.

Experiential learning, or learning through hands-on experience, provides an effective way to connect real-world management scenarios with classroom concepts (Kolb 2014). Although experiential learning has been implemented in weed science classrooms, existing laboratory exercises typically focus on isolated interactions or single-species dynamics (e.g., Gallagher et al. 2007; Gibson and Liebman 2003a; b; Gibson and Liebman 2004). These activities effectively demonstrate key weed biology and crop competition concepts but often fall short of exposing students to multispecies interactions and the complex influences of management on entire weed communities.

To improve students' understanding of the ecological principles of integrated weed management, we developed the *Weed Communities and Management* laboratory exercise to

demonstrate how management systems shape the assembly of weed communities. By seeding pots with identical weed communities and applying contrasting management filters, mimicking organic, conventional, and unmanaged systems, students learned how species-specific responses to management influence community assembly outcomes. We paired this hands-on learning with a manuscript-style writing assignment, enabling students to synthesize ecological concepts, analyze and interpret their results, and practice communicating scientific findings.

Our objectives in this paper are to (1) describe the design and implementation of the *Weed Communities and Management* laboratory exercise, (2) illustrate how simulated cropping systems influenced weed community assembly across two universities and multiple student cohorts, and (3) assess how the exercise affected student understanding of ecological weed management, systems-level thinking, and scientific writing.

Materials and Methods

Experimental Design

The *Weed Communities and Management* laboratory exercise was implemented in greenhouse facilities during the Fall 2023 and 2024 semesters in Weed Biology and Management courses at Cornell University in Ithaca, NY, and Montana State University in Bozeman, MT. Over 100 junior and senior standing undergraduate, predominately majoring in agricultural or environmental sciences, and graduate students participated across both institutions and years. The exercise was conducted mid-semester, after students had been introduced to weed identification, principles of weed management, plant functional traits, and community assembly theory, ensuring they had sufficient conceptual background to interpret observed community assembly processes and patterns.

The experiment simulated three agricultural systems; an organic vegetable farm, a conventional small-grain farm, and an unmanaged field, using five treatments (Figure 1): (1) an unmanaged control (i.e., a weedy roadside) with no fertility inputs or weed management; (2) a conventional small-grain system in the fallow phase; (3) a conventional small-grain system in the crop phase; (4) an organic vegetable system in the fallow phase; and (5) an organic vegetable system in the crop phase.

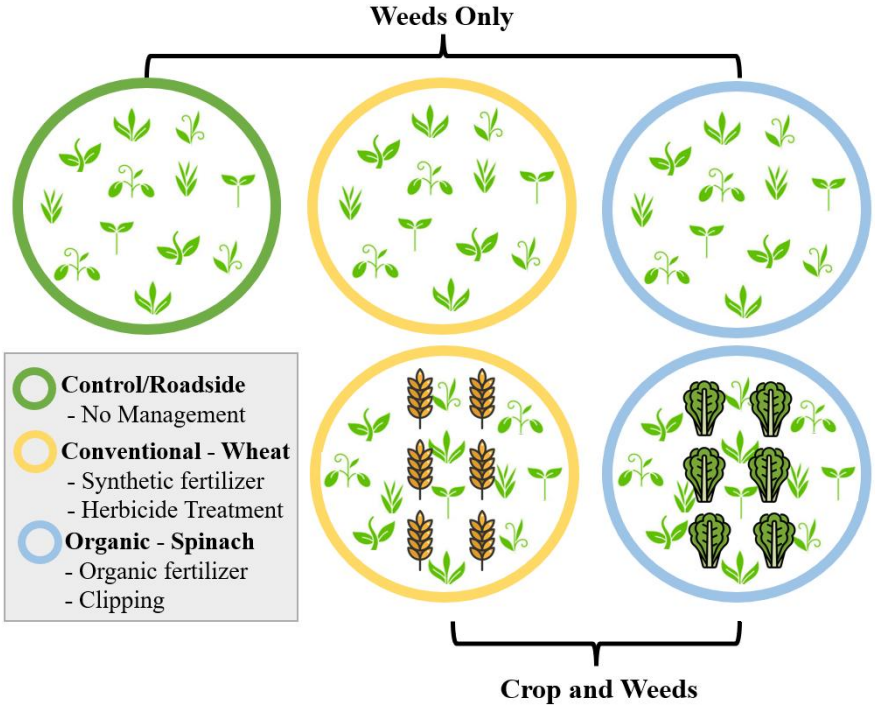


Figure 1: Experimental design of the *Weed Communities and Management* laboratory exercise. All pots were seeded with the same weed community and assigned to one of five treatments representing three systems: an unmanaged control, a conventional small-grain system (fallow and crop phases), and an organic vegetable system (fallow and crop phases). Conventional treatments received synthetic fertilizer and a postemergence 2,4-D application, whereas organic treatments received organic fertilizer and weed control via clipping.

Experimental units consisted of pots (2.54 L volume; 11cm diameter) filled with a uniform greenhouse growing medium composed of peat moss, vermiculite, and perlite mixed at approximately 1:1:0.5. Pots were maintained under controlled greenhouse conditions with a 16-h photoperiod and day/night temperature set points of 22 C and 18 C, respectively.

All pots were seeded with the same weed community to standardize propagule pressure across treatments. The weed community consisted of four seeded annuals: redroot pigweed (*Amaranthus retroflexus* L.), cheatgrass (*Bromus tectorum* L.), field pennycress (*Thlaspi arvense* L.), and velvetleaf (*Abutilon theophrasti* Medik.), and two rhizomatous perennials, Canada thistle [*Cirsium arvense (*L.) Scop.] and quackgrass [*Elymus repens* (L.) Gould]. Species were selected to represent variation in life history (annual vs. perennial), functional group (grass vs. broadleaf), and propagule traits (large- vs. small-seeded vs. rhizomes), allowing students to evaluate how management-driven filters interact with plant traits to shape weed community assembly. Annual species were planted at a density of 20 seeds per species per pot, while perennial species were planted using two 10-cm rhizome segments per species per pot, planted at a depth of 5 cm. Seeds of *A. theophrasti* were planted at approximately 2.5 cm depth, while *B. tectorum, T. arvense, A. retroflexus,* spring wheat and spinach were planted at approximately 1.25 cm depth.

In the crop-phase treatments, spring wheat was planted to mimic a conventional system while lettuce was planted to represent an organic vegetable system. Fertility inputs were applied at planting according to the system. Conventional treatments received a controlled-release synthetic fertilizer (14-14-14 N-P-K) applied at a rate of 55 g pot-^{1}, while organic treatments received organic nitrogen inputs in the form of a liquid fish emulsion fertilizer

(5-1-1 NPK) applied at a rate of 2 tsp pot-1 diluted in 0.95 L (1 qt) water. Weed management was applied once three weeks after planting: conventional treatments received a selective postemergence application of 2,4-D, organic treatments were managed by clipping weeds at the soil surface to simulate mowing or grazing, and unmanaged controls received no weed management.

Students worked in groups of three to four, with each group responsible for pot establishment, fertilization, weed management (except the postemergence application of 2,4-D which was done by the instructors), and data collection for one complete set of five treatment pots. Weed community composition was assessed by students at two points on data sheets where students recorded species-level abundance for all weeds and crops in each pot (Figure 2) immediately prior to weed management (~three weeks after planting), and three weeks after weed management. At the second collection, students also harvested all aboveground weed and crop biomass by species. Biomass samples were oven-dried at 65 C for approximately one week and weighed.

Data Collection: Pre-Weed Management / At Harvest

Group Members:

Please record the abundance of each species and crop in your group's pots.

- Treatment 1. Control/unmanaged field: no management
- Treatment 2. Conventional small grain farm, fallow phase: weeds only
- Treatment 3. Conventional small grain farm, crop phase: weeds and wheat
- Treatment 4. Organic vegetable farm, fallow phase: weeds only
- Treatment 5. Organic vegetable farm: weed and crops

	Treatment 1	*Treatment 2*	*Treatment 3*	*Treatment 4*	*Treatment 5*
Abutilon theophrasti					
Amaranthus retroflexus					
Bromus tectorum					
Cirsium arvense					
Elymus repens					
Thlaspi arvense					
Crop Wheat	**No Data Collected**	**No Data Collected**		**No Data Collected**	**No Data Collected**
Crop Spinach	**No Data Collected**	**No Data Collected**	**No Data Collected**	**No Data Collected**	

Figure 2: Data collection sheet used by students to record species-level abundance of weeds and crops in each treatment before and after weed management. Students recorded counts for all weed species and crops present in each pot across the five experimental treatments.

Statistical Analysis and Scientific Writing Assignment

To reinforce scientific communication skills, the laboratory exercise culminated in a manuscript-style lab report modeled after *Weed Science*. Students prepared an abstract, introduction, materials and methods, results, and discussion, supported by peer-reviewed literature. This approach is similar to other experiential weed science laboratory exercises that integrate experimentation with manuscript-style writing (Gibson and Liebman 2003a; bb; Gibson and Liebman 2004). Although experimental data were collected collaboratively, all scientific manuscripts were prepared individually.

Students analyzed weed communities using species-level abundance and biomass data by examining species abundance, species richness, and Shannon's diversity index (H′) using the pooled class data. As part of the assignment, students compared weed communities before and after management and summarized treatment effects using tables and a minimum of three figures. Students were encouraged to explore additional species- or crop-specific patterns to support their interpretations. Students were introduced to data analysis using Excel during guided in-class sessions, where calculations and data visualization approaches were demonstrated. Students could then apply these methods using Excel or, if preferred, statistical software (e.g., R), depending on their prior experience and formal statistical testing beyond descriptive comparisons was optional.

The writing assignment was integrated into the laboratory exercise and supported through structured, in-class instruction. Class meetings were dedicated to guiding students through data organization, calculation, and interpretation of biodiversity metrics prior to independent analysis. During these sessions, instructors provided step-by-step instruction on calculating species abundance, biomass, species richness, and Shannon diversity, and on interpreting these metrics in the context of weed community assembly. Students were also provided with structured guidelines outlining required analyses and figures for their manuscript, including comparisons of community metrics across treatments and time points. These activities ensured that all students had a consistent analytical framework before conducting their own analyses.

Additional instructional sessions focused on scientific writing, including organization of manuscript sections, clarity and conciseness in results reporting, and effective integration and citing of peer-reviewed literature. Students submitted an initial draft of their manuscript and

received detailed written feedback from the instructors. Students then revised and resubmitted their manuscripts, allowing them to engage directly in the iterative process of scientific writing and revision. This scaffolded approach was designed to help students develop both ecological reasoning and professional scientific communication skills.

To further evaluate treatment effects and visualize patterns in weed community composition across all experimental replicates, more in-depth analyses were conducted in R by the authors of this paper (R Core Team 2025); however, similar analyses could also be conducted by students or instructors when adapting this exercise for other courses. Total weed abundance, Shannon diversity (H′), and total weed biomass were analyzed using analysis of variance (ANOVA) models including treatment as a fixed effect, while accounting for variation among years and universities. Model assumptions of normality and homogeneity of variance were evaluated using residual diagnostics, and no data transformations were required. For abundance and diversity, repeated-measures ANOVA was used to account for paired before and after weed management observations within pots. When treatment effects were significant, means were separated using Tukey's honestly significant difference (HSD) test ($\alpha = 0.05$). In addition, specific contrasts were used to compare conventional and organic systems averaged across crop and fallow phases.

Shannon diversity was calculated using the Shannon index implemented in the vegan package (Oksanen et al. 2022). Differences in weed community composition were assessed using non-metric multidimensional scaling (NMDS) based on Bray-Curtis dissimilarity of species abundance data. Treatment effects on community composition were tested using permutational

multivariate analysis of variance (PERMANOVA, 999 permutations), and homogeneity of multivariate dispersion was evaluated using betadisper (Oksanen et al. 2022).

With permission from Cornell University and Montana State University, student learning outcomes were assessed using pre- and post-exercise surveys consisting of five-point Likert-scale questions evaluating confidence in weed ecology concepts, community assembly, systems thinking, and scientific writing skills. Survey responses were summarized as mean values at the class level to evaluate changes in student confidence following completion of the exercise**.**

Results and Discussion

Experimental Results

Across universities and years, simulated agricultural systems resulted in contrasting weed communities. Although treatment effects varied between universities ($p < 0.001$), treatment effects were consistent across years ($p = 0.64$). No three-way interactions among Treatment, Year, and University were found ($p = 0.18$), indicating that treatment effects were directionally consistent across years and universities. Because overall treatment patterns were similar despite the variation observed between universities, data were pooled to emphasize general patterns relevant to the teaching exercise. While we cannot explain some of the results generated by the students, the overall exercise allowed them to increase their understanding of the impact of management systems on the assembly of weed communities.

Prior to the application of weed management, total weed abundance differed among treatments ($p < 0.001$) (Figure 3A). The unmanaged control supported the greatest number of individuals, averaging 37.2 ± 14.9 plants pot^{-1}. Conventional small grain systems supported the fewest individuals, averaging 20.8 ± 14.9 plants pot^{-1} in the fallow phase and 20.7 ± 15.2 plants

pot^{-1} in the crop phase, approximately 45-50% fewer individuals than the unmanaged control. Organic vegetable systems supported intermediate weed abundance, averaging 38.1 ± 11.5 plants pot^{-1} during the fallow phase and 32.3 ± 15.9 plants pot^{-1} during the crop phase. Tukey-adjusted post hoc comparisons indicated that conventional systems differed from both organic and unmanaged systems (all $p < 0.001$), whereas organic and unmanaged systems did not differ from one another (organic fallow vs unmanaged: $p = 0.998$; organic crop vs unmanaged: $p = 0.575$). No differences were detected between crop and fallow phases within conventional ($p = 0.999$) or organic systems ($p = 0.426$).

As expected, across all pots, total weed abundance declined following weed management ($p < 0.001$) (Figure 3B). The magnitude of reduction differed among treatments ($p < 0.001$). The unmanaged control had the greatest total abundance, with an average of 35.6 ± 9.1 plants pot^{-1}. Conventional systems had 14.2 ± 9.4 plants pot^{-1} in the crop phase and 15.0 ± 7.4 plants pot^{-1} in the fallow phase, representing 58-60% reductions relative to the unmanaged control. Organic systems declined to 16.7 ± 7.4 plants pot^{-1} in the crop phase and 20.2 ± 6.8 plants pot^{-1} in the fallow phase, corresponding to 43-53% reductions relative to the unmanaged control. Tukey-adjusted comparisons indicated that the unmanaged treatment differed from both managed systems ($p < 0.001$), whereas we did not find differences between the conventional and organic management treatments in the pooled analysis (all $p \geq 0.362$). Despite the lack of statistical evidence for separation among the different simulated management scenarios, a result expected in real-world scenarios (Mwangi et al. 2024), organic treatments consistently maintained a greater abundance than conventional systems across universities and years, a trend students identified when interpreting management tradeoffs in their manuscripts.

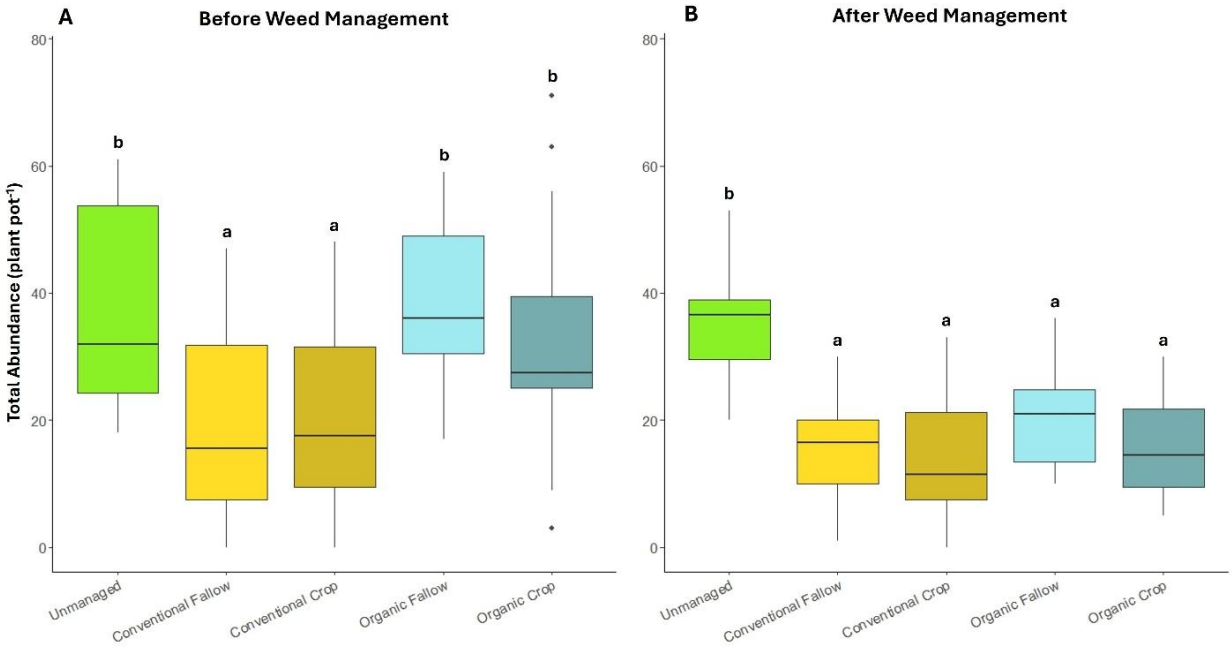


Figure 3: Total weed abundance (plants pot^{-1}) before and after weed management across five simulated management systems. Letters within each panel represent a compact letter display derived from Tukey-adjusted pairwise comparisons. Before management, conventional systems supported fewer individuals than organic and unmanaged systems. After management, the unmanaged control supported greater abundance than all managed systems, which did not differ from one another.

Shannon diversity differed among simulated agricultural systems prior to weed management ($p < 0.001$) (Figure 4A). Tukey-adjusted post hoc comparisons indicated that both conventional treatments had lower diversity than organic fallow (both $p < 0.001$) and organic crop (conventional fallow: $p = 0.006$; conventional crop: $p = 0.001$). Conventional treatments also had lower diversity than the unmanaged control (conventional fallow: $p = 0.001$; conventional crop: $p < 0.001$). Organic and unmanaged treatments did not differ (organic fallow vs unmanaged: $p = 0.733$; organic crop vs unmanaged: $p = 0.991$). Also, no differences were detected between crop and fallow phases within conventional ($p = 0.973$) or organic systems ($p = 0.444$).

Across all pots, Shannon diversity declined following weed management ($p < 0.001$), and the magnitude of decline differed among treatments ($p < 0.001$). Following weed management, Shannon diversity differed among management systems ($p < 0.001$) (Figure 4B). The unmanaged control supported greater diversity than all managed systems (all Tukey-adjusted $p < 0.001$). Organic treatments maintained greater diversity than conventional treatments (organic fallow vs. conventional fallow: $p = 0.005$; organic fallow vs. conventional crop: $p < 0.001$; organic crop vs. conventional fallow: $p = 0.034$; organic crop vs conventional crop: $p = 0.005$), whereas no differences were detected between crop and fallow phases within conventional ($p = 0.964$) or organic systems ($p = 0.968$).

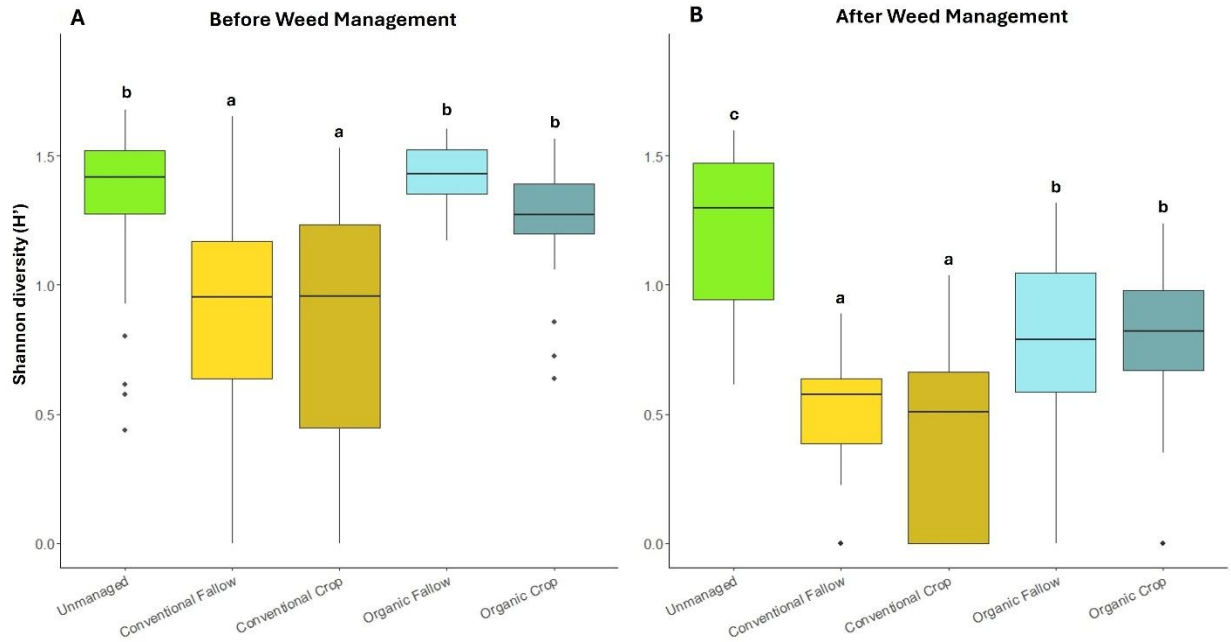


Figure 4: Shannon diversity (H`) before and after weed management across five simulated management systems. Letters within each panel represent a compact letter display derived from Tukey-adjusted pairwise comparisons. Before management (A), diversity was greater in organic and unmanaged systems than in conventional systems. After management (B), diversity was highest in unmanaged controls, intermediate in organic vegetable systems, and lowest in conventional small-grain systems.

Community composition varied among simulated agricultural systems both before (PERMANOVA: $R^2 = 0.121$, $p = 0.001$; stress = 0.145) and after weed management ($R^2 = 0.177$, $p = 0.001$; stress = 0.108) (Figure 5). Treatment-associated variation was greater after management, as reflected by increased explained variation and clearer separation among groups in ordination space. Multivariate dispersion differed among treatments before weed management ($p = 0.001$) and after weed management ($p = 0.016$).

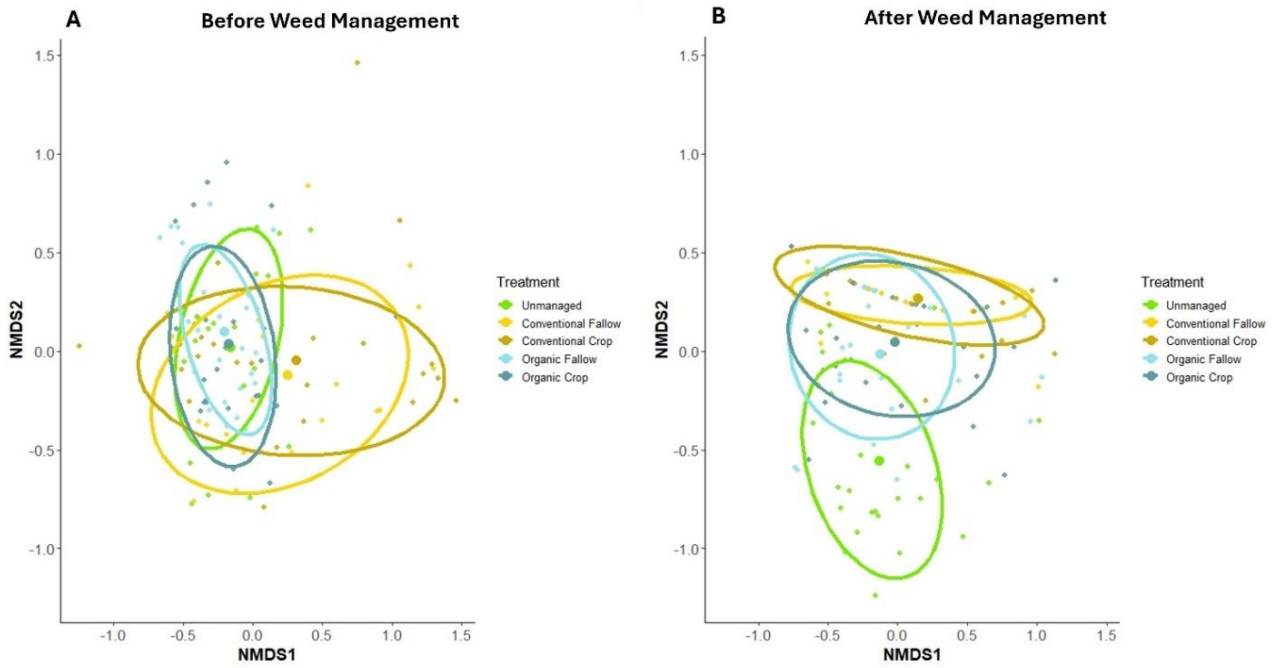


Figure 5: Non-metric multidimensional scaling (NMDS) ordination of weed community composition before and after weed management based on Bray-Curtis dissimilarity of individual weed counts. While community composition varied among treatments before management (A) (PERMANOVA: $R^2 = 0.121$, p = 0.001; stress = 0.145) and after weed management (B), we observed a greater separation among simulated systems following management ($R^2 = 0.177$, p = 0.001; stress = 0.108).

At the end of the experiment, total weed biomass differed across treatments (Figure 6), after accounting for university and year effects ($p < 0.001$). Unmanaged systems consistently produced the greatest weed biomass. In contrast to patterns observed for weed abundance and

Shannon diversity, total weed biomass did not differ between conventional small-grain and organic vegetable systems ($p = 0.233$), nor between crop and fallow phases within conventional ($p = 0.435$) or organic systems ($p = 0.373$). These results indicate that while weed management reduced total biomass relative to the unmanaged control, differences in biomass among managed cropping systems were comparatively small.

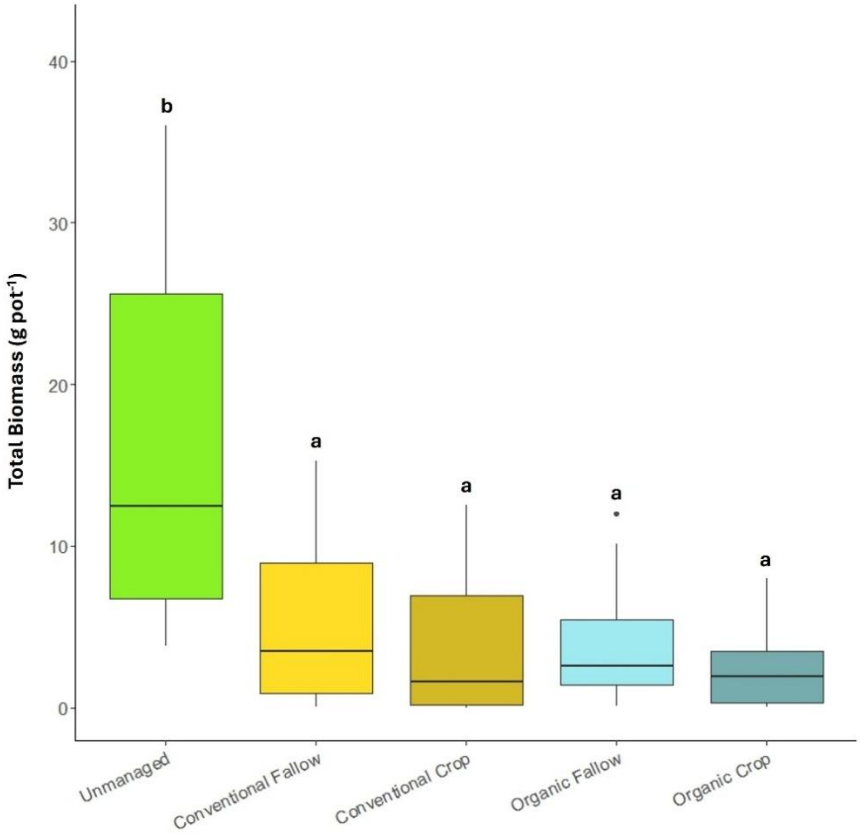


Figure 6. Total weed biomass (g pot^{-1}) at harvest across five simulated management systems. Letters represent a compact letter display derived from Tukey-adjusted pairwise comparisons. Total biomass differed among treatments after accounting for university and year effects ($p < 0.001$). The unmanaged control supported the greatest biomass, whereas all managed systems did not differ from one another.

Student Results

Across both universities and years, 125 students completed the pre-laboratory exercise survey and 103 completed the post-laboratory exercise survey. Students reported increased

confidence across all assessed learning objectives following completion of the weed community assembly laboratory exercise and the associated manuscript-style writing assignment (Table 1). The largest learning gains occurred for weed ecology concepts, particularly those related to ecological interactions and community assembly (Figure 7). Confidence increased most strongly for differences in competitive ability among weed species (+1.35), weed community assembly (+1.30), weed species identification (+1.30), and calculating diversity indices (+1.29). Moderate but consistent gains were observed for scientific writing skills, including formatting a scientific manuscript (+0.88) and writing a scientific abstract (+0.80). Smaller increases (<0.80) were observed for interpreting results, presenting data graphically, and properly citing literature, though post-activity confidence for these skills remained high overall.

Table 1: Students' self-reported confidence before and after completing the weed community assembly laboratory exercise and associated manuscript assignment. Confidence was assessed using a five-point Likert scale (1 = very unconfident, 2 = fairly unconfident, 3 = neutral, 4 = fairly confident, 5 = very confident). Values represent means of responses pooled across universities and years.

Learning Category	Perceived knowledge of...	Pre	Post	Gain
Scientific Writing	Format of a scientific manuscript	3.17	4.05	+0.88
	Writing a scientific abstract	3.25	4.05	+0.80
	Presenting scientific data in graphical/tabular format	3.53	4.07	+0.54
	Concisely describing the materials and methods of an experiment	3.82	4.3	+0.48
	Writing out the results of an experiment	3.59	4.07	+0.48
	Analyzing research data	3.53	3.93	+0.40
	Interpretation of results in a written discussion	3.61	4.01	+0.40
	Ability to gain and interpret information from scientific literature	3.74	4.07	+0.33
	Properly citing literature both in-text and in a references section	3.94	4.22	+0.28
Weed Ecology	Differential weed species competition	2.43	3.78	+1.35
	Weed community assembly in agroecosystem	2.42	3.72	+1.30
	Weed species identification	2.70	4.00	+1.30
	Calculating diversity indices	2.11	3.41	+1.29
	Variable impacts of management on weed species	2.98	4.11	+1.12
	Plant community assembly	2.69	3.74	+1.05
	Differences between management in conventional and organic agricultural systems	3.55	4.32	+0.77

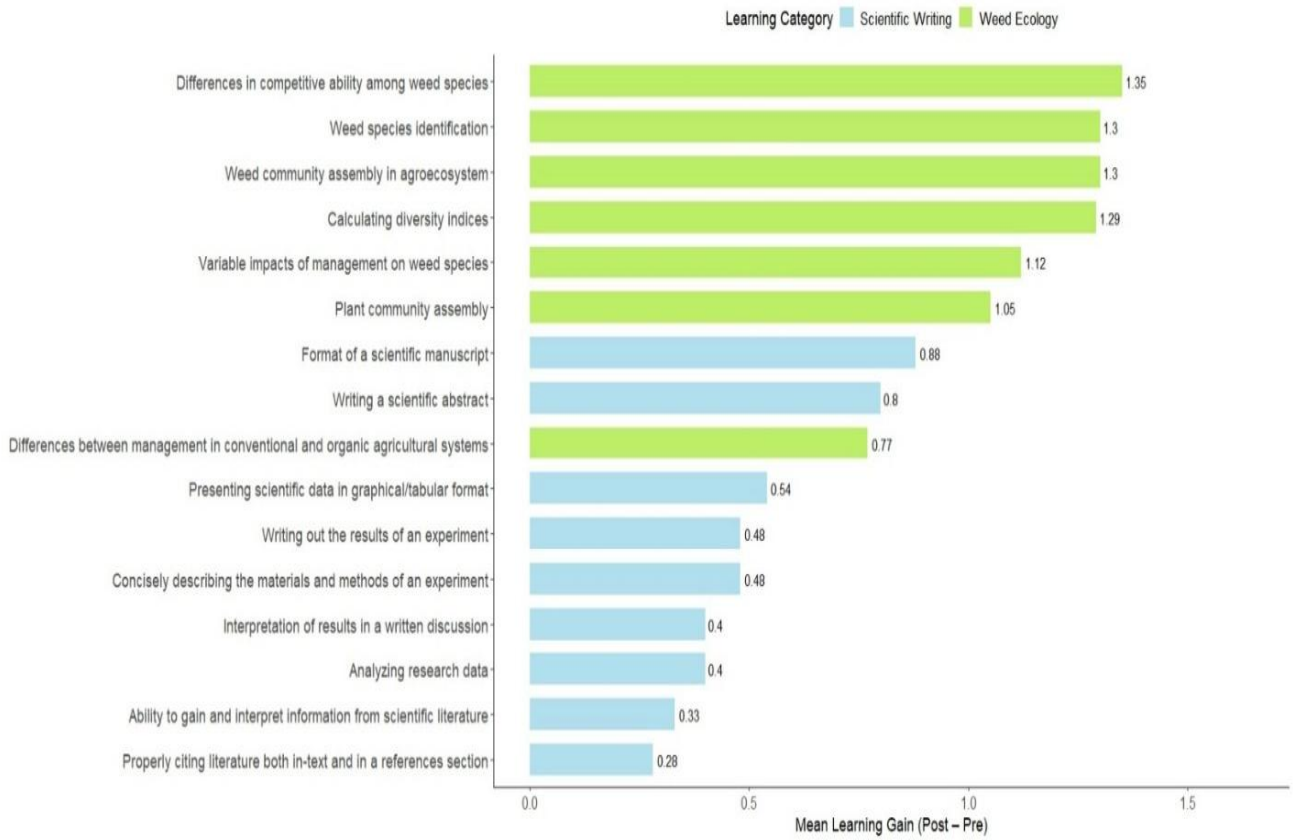


Figure 7. Mean learning gains (post-activity minus pre-activity Likert scores) for students' self-reported knowledge across weed ecology and scientific writing learning objectives following completion of the weed community assembly laboratory exercise. Higher values indicate greater increases in student confidence.

Student manuscripts demonstrated that participants were able to interpret experimental results using multiple ecological theories and systems-thinking approaches. Students framed weed community dynamics through the lens of community assembly and environmental filtering, recognizing that management practices act as selective pressures determining which species persist within agroecosystems. For example, one student explained, by citing Benaragama et al. (2019), that *"management practices act as key environmental filters that shape weed communities, determining which species establish and thrive."* Similarly, a student cited Booth and Swanton (2002) to justify that *"environmental factors eliminate species that lack the traits*

necessary to survive in a species pool; as these traits are filtered, so too are the species that lack them."

Students frequently used trait-based reasoning to explain differences among treatments and to interpret how management practices influence weed community assembly. Many manuscripts framed agricultural practices as environmental filters that interact with species traits to determine which weeds are present within cropping systems. For example, one student explained that *"these treatments and experimental setups can be thought of like filters, as postulated by Ryan et al. (2010)."* Other students further connected these filters to functional traits that influence species responses to management practices. Referencing Schumacher et al. (2018), one student wrote that *"weed community assembly is a theory of the development of a weed population as filtered by biotic and abiotic factors, such as crop row spacing, nutrient availability, tillage, and pesticides."* Students then applied these concepts to interpret the patterns observed in the experiment. For example, one student noted that *"the conventionally managed community applied selective pressure to this weed community, eliminating the broadleaf weedy species…(and) the community switched to favor the grasses."* These interpretations reflected an understanding that agricultural practices structure weed communities by favoring species with traits best suited for specific disturbance regimes, consistent with findings from trait-based weed ecology studies (Fried et al. 2012).

Students applied concepts of competition to explain patterns observed in the experiment. Several manuscripts emphasized the role of crop presence as a biotic filter influencing weed success. As one student observed, *"a filter that affected the weed community assembly was the presence of crops …when crops were present, the weeds were suppressed slightly because crops*

were taking up resources and space in the community." Students therefore recognized that crop-weed competition can significantly influence community structure and weed abundance, in agreement with Gaba et al. (2018); Gibson et al. (2017); Weiner et al. (2001) and Wilson et al. (1995). Some students further interpreted these patterns using the theory of asymmetric competition. For example, one student cited Weiner (1990) to explain that *"asymmetric competition is an ecological theory in which larger individual plants gain a disproportionate amount of nutrients compared to the smaller individuals surrounding them."* Students used this concept to explain how crops, once established, can outcompete neighboring weeds by capturing a greater share of limiting resources such as light, nutrients, and space, to explain observed differences in communities.

Students also used niche theory to explain patterns in weed community composition. Several manuscripts discussed how differences in environmental conditions and management practices can create distinct ecological niches that influence which species establish and persist within cropping systems. For example, one student cited Benaragama et al. (2019) and Cordeau et al. (2021) to explain that *"different agricultural management systems, e.g., conventional, organic, tillage, and no-till, can result in different niches and thus weed community assemblies."* Students used this concept to interpret differences in species composition among treatments, recognizing that management practices alter resource availability and disturbance regimes, thereby shaping the niches available to different weed species.

Another common theme across student manuscripts was the ecological role of weed diversity in shaping crop-weed competition. Several students suggested that the composition and diversity of weed communities can influence the strength of weed-crop competition. For

example, one student cited Storkey and Neve (2018) to explain that *"weed seedbank diversity can be used as a measure of cropping system sustainability, and a more diversified weed community may be less competitive with crops."* Similarly, another student referenced Schumacher et al. (2018), noting that *"modern agriculture has effectively decimated weed diversity in favor of a few dominant species. This has created more competition between weeds and crops, opened avenues for invasive species to enter the system, negatively affected beneficial insect populations, and lowered available genetic resources."* These responses indicated that students assessed weeds not simply as individual competitors with crops, but as members of ecological communities whose composition can influence competitive outcomes. This interpretation aligns with ecological research suggesting that weed community diversity can shape crop-weed competition and broader agroecosystem dynamics (Pollnac et al. 2009).

Building on the concept of weed diversity, students further discussed how managing weed communities involves trade-offs between weed suppression, biodiversity, and long-term system resilience (Adhikari et al. 2019). Students frequently discussed how highly selective management practices can result in unintended consequences such as species dominance. For example, one student referenced Bàrberi (2002), noting that "*the presence of a more diverse weed community may foster greater ecosystem resilience, enhancing soil health and increasing pest regulation through a variety of plant species that provide food and habitat for beneficial organisms. However, the trade-off is that these systems may experience higher levels of competition between weeds and crops, potentially reducing crop yields."*

Several students further explored the trade-off between weed community composition and ecosystem services. For example, one student referenced Esposito (2023), explaining that *"if*

a weed community does not cause major crop yield or quality losses, weed management actions can be reduced and some weeds conserved for ecosystem service provisioning and maintenance of biodiversity. Promoting neutral weed communities is therefore an effective method of enhancing the sustainability and long-term productivity of agricultural systems."

Students also proposed solutions to managing weeds in agroecosystems to limit filters that may select for more competitive weeds. Specifically, many students focused on integrated weed management approaches, combining multiple strategies to balance productivity and ecological sustainability. One student wrote that *"a mixture of multiple methods, or an integrated approach to weed management, is the most effective form of management,"* a central tenet of integrated weed management (Swanton and Weise 2017). Others emphasized the importance of adaptive management based on community composition and ecological context, noting that *"proper monitoring must be done to ensure that correct control methods are applied based on a system's community strengths and weaknesses,"* a concept presented in Smith et al. (2023) and discussed during lectures.

Student manuscripts also demonstrated strong development of scientific reasoning skills, particularly through the interpretation of unexpected results and the evaluation of experimental limitations. Several students described how their observations challenged their initial assumptions regarding the relative effectiveness of conventional and organic management strategies. For example, one student noted that *"to my surprise… organic systems with both crops and weeds had the lowest weed biomass,"* contradicting initial predictions that herbicide-based management would provide the greatest weed suppression.

Other students critically evaluated the experimental design and considered how greenhouse conditions might differ from real agricultural systems. One manuscript noted that *"it is much easier to remove all velvetleaf seedlings in a small pot than it is in a 100-acre farm,"* highlighting the challenges of scaling experimental findings to field conditions. Together, these responses indicate that students were able to integrate ecological theory, interpret experimental data, and critically evaluate the implications of weed management strategies within agricultural systems.

Discussion

Ecologically based weed management emphasizes understanding the processes regulating weed communities rather than focusing solely on eliminating individual weed species, which represents an important shift in the conceptual framework used to manage weeds (MacLaren et al. 2020). This *Weed Communities and Management* laboratory exercise successfully helped undergraduate and graduate students comprehend weed community assembly, a foundational concept underlying ecologically-based weed management. Across universities and years, simulated cropping systems produced distinct weed communities, highlighting how management decisions influence weed species establishment and persistence through selective filters imposed by weed control practices, nutrient inputs, and crop-weed competition (Booth and Swanton 2002).

In addition to illustrating ecological weed management concepts, this laboratory exercise produced measurable improvements in student learning outcomes. Students reported increased confidence across both weed ecology and scientific writing concepts following completion of the exercise and associated manuscript assignment. These improvements suggest that engaging

students directly with experimental learning on weed communities can strengthen their understanding of ecological interactions that are often difficult to convey through lectures alone. By interpreting and communicating weed community-level responses to management decisions, students were able to connect ecological theory with agroecosystem dynamics and management. Notably, because participants included both undergraduate and graduate students with varying levels of prior experience in weed and ecological sciences, differences in baseline knowledge may have influenced the magnitude of reported learning gains.

Equipping students with systems thinking skills is essential for preparing them to address emerging challenges in sustainable agriculture (Francis et al. 2011). While other experiential learning activities in weed science that focus on individual crop–weed interactions or weed biology concepts are effective for teaching foundational principles (e.g., Gallagher et al. 2007; Gibson and Liebman 2003a; b; Gibson and Liebman 2004), they often fail to capture agroecosystem complexity. As a result, students have limited opportunities to explore how weed ecology concepts play out within the multidimensional agricultural systems that they will encounter in their professional careers. This laboratory exercise addressed this need by allowing students to examine how different management strategies shape weed community dynamics. Within the experiment, the simulated cropping systems produced shifts in weed communities like those observed in agricultural systems (Barroso et al. 2015; Smith and Gross 2007). Most notably, the simulated conventional small-grain systems consistently had lower weed abundance and diversity than the organic vegetable systems. Despite these differences in weed abundance and diversity, total weed biomass did not differ between the systems. These patterns reflect dynamics commonly observed in agricultural systems, where organic management practices

facilitate greater weed abundance and diversity compared with conventional systems (Mwangi et al. 2024). Through this exercise, students were introduced to the concept that increased weed diversity in organic systems may mitigate crop yield losses by reducing dominance of highly competitive weed species and promoting resource partitioning among species rather than direct competition with crops for a single resource pool (Adeux et al. 2019; Smith et al. 2010; Storkey and Neve 2018). These dynamics may help explain why, despite greater weed abundance, yield losses in organic systems are often comparable to or lower than those observed in conventional systems (Ryan et al. 2010). Our exercise allowed students to observe this relationship directly and interpret it using concepts introduced in lecture and supported through peer-reviewed literature, thereby learning the importance of managing weeds at the community level (Storkey and Neve 2018). These direct connections between observed community-level patterns and ecological interpretation likely contributed to the increases in student confidence in weed community assembly, ecological interactions, and data interpretation reported in the post-exercise survey.

While the simulated cropping systems reproduced patterns commonly observed in agricultural systems, the results did not always align with outcomes expected from field conditions or controlled greenhouse experiments. This discrepancy is expected given that the exercise was implemented by students as part of a laboratory course rather than as a formal research experiment. As a result, variability in plant identification and weed removal may have contributed to differences among treatments. These differences do not diminish the value of this laboratory exercise as a teaching tool, as it provides novel opportunities for students to critically evaluate how experimental systems differ from real-world agroecosystems and more controlled

research studies, while reinforcing the complexity of ecological processes influencing weed community assembly.

A key component of this laboratory exercise was its emphasis on experiential learning. There is substantial evidence that experiential learning activities improve student learning outcomes (Burch et al. 2019), and such approaches are particularly valuable for helping students understand agroecosystems and the interacting ecological, social, and management processes that shape them. Experiential learning allows students to navigate the uncertainty and complexity inherent in agricultural systems by interpreting interactions among ecological processes such as crop-weed interactions and linking community assembly with management decisions (Francis et al. 2011; Stein 2025). Previous studies have similarly demonstrated the value of active learning approaches for teaching weed science concepts (Berríos-Ortiz et al. 2026; Gallagher et al. 2007; Menalled et al. 2024; Stein 2024).

An additional benefit of this exercise was the integration of a manuscript-style writing assignment, which required students to interpret their experimental results and support their conclusions using peer-reviewed literature. Scientific writing encourages students to synthesize complex concepts and apply them to experimental observations (Emig 1977), strengthening their ability to communicate ecological findings. Despite the learning opportunities scientific writing provides, undergraduate students have repeatedly reported lacking chances to practice it within agricultural and environmental science curricula (Jerde and Taper 2004; Motavalli et al. 2003). By requiring students to organize their results into a manuscript structure, this assignment encouraged them to interpret experimental data, connect their findings to ecological theory and management decisions, and engage critically with the scientific literature.

The structure of the laboratory exercise can be adapted to meet a range of course objectives and student skill levels. In this course, students conducted basic analyses of their experimental data using spreadsheet software, including calculations of weed abundance, species richness, and Shannon diversity. Additional statistical analyses used to summarize patterns across universities and years were conducted separately for the purposes of this manuscript and were not part of the student assignment. However, instructors implementing this activity in other courses may choose to incorporate more advanced analyses depending on course learning objectives and student familiarity with statistical methods. For example, students could analyze the data using statistical software such as R (R Core Team 2025) to explore treatment effects, community composition, or diversity patterns in greater depth. The experiment could also include additional measurements such as crop yield to more directly illustrate how weed community composition influences crop performance. Instructors may also incorporate trait-based analyses (Gaba et al. 2017) by having students classify weed species according to functional traits, allowing them to explore how management filters select for specific ecological strategies.

By connecting management practices to weed community assembly and requiring students to interpret these patterns using ecological theories, the *Weed Communities and Management* laboratory exercise provides a practical framework for teaching ecological weed management. Through a combination of experiential learning and scientific writing, this exercise presents students with an opportunity to engage directly with the ecological processes shaping weed communities and to examine weed management at the systems level, where interactions among crops, weeds, and management practices create complex outcomes. The laboratory

exercise helps address a gap in weed science education by encouraging students to interpret agroecosystem dynamics rather than focusing solely on individual weed species. As ecological approaches to weed management become increasingly important (MacLaren et al. 2020), it is critical to prepare future weed scientists and land managers through educational activities that emphasize systems thinking and experiential learning within agroecosystems.

Practical Implications

The *Weed Communities and Management* laboratory exercise provides instructors with an approach for teaching ecological weed management by allowing students to explore the complexity of agroecosystems in a classroom setting. Through simulated cropping systems representing organic vegetable production, conventional small grain production, and unmanaged systems, students can directly observe and reflect on how management practices influence weed communities through the process of community assembly. The manuscript-style assignment further reinforces students' scientific communication skills by requiring them to interpret ecological patterns and present their findings in the format of a scientific research paper. Because the exercise uses relatively simple materials and greenhouse space, it can be readily implemented in undergraduate or graduate weed science courses and adapted to different class sizes, course levels, or regional weed communities. This framework helps students connect ecological concepts to real-world weed management decisions, better preparing them for future careers as weed scientists and land managers.

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CHAPTER SIX

SYNTHESIS AND CONCLUSION

Ecological approaches to weed management emphasize understanding and manipulating interactions among crops, weeds, and agroecosystem processes to improve sustainability (Liebman et al. 2001; MacLaren et al. 2020). This dissertation integrates field experiments, controlled-environment studies, on-farm surveys, and experiential learning to advance ecologically based weed management (EWM) in small-scale organic vegetable systems. Specifically, this work evaluated the critical period of weed control (CPWC) in carrots using both yield and quality metrics, assessed how elevated atmospheric CO_2 alters crop-weed interactions and CPWC length, characterized weed community functional diversity across Montana organic vegetable farms using trait-based approaches, and developed an experiential learning exercise to improve student understanding of weed community assembly and EWM. Together, these studies address key knowledge gaps limiting the application of ecological principles in weed management and provide insights for improving decision-making in organic and diversified agricultural systems.

Integrating weed management across scales: from individuals to communities to classrooms

This dissertation demonstrates that weed management outcomes are shaped by processes operating across multiple scales, from individual plant interactions to weed community processes. The CPWC studies emphasize how crop-weed competition directly influences management timing and the resulting carrot yield and quality. The concept of the CPWC has long been used to guide efficient weed management by identifying the period when crops are

most sensitive to competition based on yield (Knezevic et al. 2002; Knezevic and Datta 2015). By incorporating both yield and quality into determining the CPWC, this work expands the traditional framework to better reflect the realities of vegetable production, where marketability and value-added potential are indispensable components of revenue for growers (Gamba et al. 2021). More broadly, this work also highlights the value of integrating a food systems perspective when considering crop-weed competition research, where management decisions are evaluated not only based on yield outcomes, but also on their implications waste reduction and value-added opportunities for weed impacted produce.

The controlled-environment study further demonstrated that crop-weed competition interactions and management recommendations shift under changing environmental conditions, being the first formal evaluation on the impact that predicted CO_2 levels could have the length of the CPWC. These results align with broader findings that rising atmospheric CO_2 can modify plant growth, resource allocation, and competitive dynamics among species (Korres et al. 2016; Poorter and Navas 2003; Ziska 2001). Specifically, the reduced CPWC duration for radish root yield and extended CPWC for shoot yield demonstrates that future weed management recommendations may diverge depending on production goals. These findings highlight that climate change introduces an additional layer of complexity to weed management, and that existing recommendations to minimize weed competition will need to be adapted, requiring strategies that account for both environmental changes and crop-specific responses.

While the CPWC studies focused on individual crop-weed competition, the farm-scale survey addressed a critical knowledge gap by characterizing weed communities in organic vegetable systems, where limited research has been conducted, particularly in the Middle

Rockies region. Using a trait-based approach, this work moved beyond species-level descriptions to evaluate the functional composition of weed communities and how they vary (Navas 2012; Gaba et al. 2017). Results showed that weed community composition and functional traits were more strongly associated with farm- and year-level variation than with crop identity. These findings highlight that weed impacts in organic vegetable systems cannot be addressed through crop-level interactions alone and must be considered within the broader context of farm-level management and environmental variability. By demonstrating that management acts as a primary ecological filter, this work reinforces the importance of managing weed communities, rather than individual species for successful ecologically based weed management (MacLaren et al. 2020).

The educational component reinforces this framework by demonstrating that different management systems produce distinct weed communities, and that students can connect these patterns to ecological theory and management decisions. These findings highlight the value of experiential learning, particularly for understanding complex processes, such as weed community assembly, that are difficult to convey through lecture alone. By engaging directly with how management shapes weed communities, this work supports the development of systems-thinking skills that are essential for applying ecologically based weed management in practice.

Management Implications

The findings of this dissertation have several important implications for the development and application of EWM in organic vegetable systems. First, incorporating crop quality into weed management decision-making is critical. Traditional approaches that rely solely on yield loss thresholds may overlook important economic aspects of crop production, especially for

diversified and direct-market vegetable systems. Expanding CPWC, and other weed-crop competition frameworks, to include quality metrics provides a more comprehensive basis for management recommendations. Second, weed management recommendations must account for the impacts of climate change. The observed shifts in the CPWC under elevated CO_2 indicate that the duration of vulnerability of crops to competition from weeds is likely to change under future climate conditions. These changes may not be uniform across crops or production goals, emphasizing the need for flexible, adaptive management approaches. Third, weed management should be approached at the community level. The dominance of farm-level effects on weed community structure suggests that consistent management practices and environmental conditions play a larger role in shaping communities than crop identity alone. This supports a whole-farm approach to managing weed communities Finally, preparing future scientists and land managers to apply ecological principles is essential for the successful implementation of EWM, process that requires improved education and training. The laboratory exercise demonstrates that experiential learning can effectively build system-thinking skills and improve understanding of ecological processes and the scientific process.

Future research directions

This work highlights several key areas for future research. First, evaluating the CPWC across crops, climates, and management systems will improve the applicability of CPWC based recommendations. Future work could also examine legacy effects, such as how prior cover crops influence weed community composition and subsequent competitive dynamics, and how these shifts alter windows of crop vulnerability to competition. Additionally, further research is needed to assess mismatches between management recommendations based on yield versus quality

across a wider range of vegetable crops and investigate opportunities for weed-impacted produce.

Second, research should focus on how crop-weed interactions and management timing are impacted by climate change factors beyond CO_2, including temperature and precipitation variability. Research should also evaluate how species with different resource allocation strategies respond to these changes, especially crops that do not exhibit strong belowground sinks like radish. Continued research in this area is essential to understanding how crop-weed competition-based management recommendations may shift under future conditions.

Third, linking weed community composition and functional traits to crop performance remains an important research gap. While this dissertation characterized weed communities using trait-based approaches, future work should directly connect these patterns to crop yield and quality outcomes, while also considering trade-offs with ecosystem services. Additionally, more research is needed to explicitly link specific management practices to the selection pressures they impose, particularly in diversified organic vegetable systems.

Conclusion

This dissertation demonstrates that effective weed management in small-scale organic vegetable systems requires an ecological perspective that integrates processes across scales. By combining experimental, observational, and educational approaches, this work advances understanding of how weed management can be improved through ecological principles. As agricultural systems face increasing pressures from climate change, labor constraints, and the need for sustainable intensification, adopting ecologically based approaches will be essential for

enhancing resilience, improving management recommendations, and supporting the important role that organic and diversified vegetable cropping systems play in our food systems.

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