INVESTIGATING THE EFFICACY AND SAFETY OF SULFENTRAZONE FOR WEED CONTROL IN CABBAGE AND BROCCOLI

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ABSTRACT

Cabbage (*Brassica oleracea* var. capitata L.) and broccoli (*Brassica oleracea* var. italica L.) are important agricultural commodities nationwide, including in New York (NY) and New Jersey (NJ). The management of pests, which includes weeds, is critically important for maximizing both yield quantity and quality. Weeds can directly reduce head numbers and weights through interspecific competition for shared resources. Additionally, weeds can indirectly impact yields by serving as an alternate host for pests and pathogens, by impeding harvest operations, and when weed seeds contaminate cabbage heads. Many fresh market and processing growers rely heavily on the use of herbicides to suppress weeds. Currently, there are relatively few active ingredients available for use in *Brassica* crops. Additionally, most registered products have limited spectrums of control that reduce their stand-alone efficacy. Consequently, the evaluation and registration of new herbicides has been and continues to be a high priority for cabbage and broccoli growers. Sulfentrazone, a protoporphyrinogen oxidase (PPO) inhibiting herbicide with both early postemergence and residual activity, has been registered for use in cole crops in several states, although published performance data is minimal. In addition to controlling annual broadleaf and some grass species, sulfentrazone could benefit to growers as it could help to enhance the suppression of difficult to control perennial weed species like yellow nutsedge (*Cyperus esculentus* L.) and field bindweed (*Convolvulus arvensis* L.).

In 2021 and 2022, researchers at Cornell University and Rutgers University initiated small-plot research trials to evaluate the efficacy and crop safety of sulfentrazone in transplanted cabbage and broccoli. Four herbicide treatments were applied in May (Cornell) or August (Rutgers) and were replicated 4 times in each crop in a split plot design. Treatments included

oxyfluorfen (560 g ai ha^{-1} pre-transplant), sulfentrazone at a low rate (116 g ai ha^{-1}) and a high rate (233 g ai ha^{-1}) both pre-transplant, and *S*-metolachlor (715 g ai ha^{-1}) immediately post-transplant followed by (fb) oxyfluorfen (210 g ai ha^{-1}) 14 days later. Weed control, expressed as weed cover and plant density counts m^{-2}, and visual crop injury ratings were collected, weekly to bi-weekly, for 28 days after planting (DAP) and 42 DAP. Data were analyzed using PROC GLIMMIX IN SAS where location, crop, herbicide, and their interactions were main effects and year and replications nested within year were treated as random. Results of this study support that sulfentrazone has the potential to be an effective tool in a weed control program in Northeastern and Mid-Atlantic conditions for cabbage and broccoli production.

Specialty crop operations also have the highest share of labor costs as a proportion of total expenses compared to non-specialty crop operations. Hand weeding continues to play an important role in weed management programs but requires significant human labor. Immigration policies contribute to farmworker shortages, who are predominantly foreign-born and may not always be authorized to work in the US. Novel weed control technologies, which include equipment such as tractor-mounted electric weeders, vision-guided cultivators, or precision-sprayers, can reduce the inputs into weed management. Cross-disciplinary collaboration can help improve the adoption of these technologies while centering the dynamic needs of agricultural communities. High schools, colleges, and trade schools will play a role in building workforce capacity as labor demands shift in response to increased automation and mechanization in agriculture. Labor-saving, novel weed control technologies have the potential, particularly in the Northeast, to be incorporated into weed management programs to improve weed control while considering the needs of a changing workforce, especially agricultural worker health and safety.

BIOGRAPHICAL SKETCH

Laura Pineda-Bermúdez was born in 1995 in Phoenix, Arizona. She is the daughter of Maria Fernanda Bermúdez and Mauricio Pineda Román. She has a younger brother, Mario, and a lot of house plants. Laura graduated from Cornell University with a Bachelor of Science in Environmental and Sustainability Sciences in 2018, with a minor in Community Food Systems. She started working at the National Good Agricultural Practices (GAPs) Program shortly after graduation. In January 2020, through the support of the Employee Degree Program and her supervisor Betsy Bihn, she matriculated in the section of Horticulture’s M.S. degree program and joined the Sosnoskie Lab soon after.

Dedication

They say it takes a village to raise a child, but the same could be said about writing a thesis and finishing a degree. I am eternally grateful for my village, without which I could not have made it across the finish line. I dedicate this thesis to everyone who has supported me through this process.

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Chapter 1: An Introduction to Weed Management in Cabbage and Broccoli

Value of Cole Crops

Cole crops, such as cabbage and broccoli, are important agricultural commodities, worldwide. These crops are part of the mustard, or *Brassicaceae* family, and may be commonly referred to as “brassicas” (Guerena 2020). Cole crops have a long history of domestication that reaches back 6430-4278 years before present, with turnip hypothesized to be the first domesticated *B. rapa* (McAlvay et al. 2021). Although cole crops are referred to by different names, many are simply derivations of the same few species. For example, *Brassica rapa* and *Brassica oleracea,* include kale, cauliflower, bak choi, turnip, collards, brussels sprouts, kohlrabi, broccoli, and napa cabbage, to name a few (Tarlach 2021). Selection across years and cultures has also focused on the development of different characteristics (Dixon 2017). For example, although both are the same species (*B. oleracea*), cabbage has tightly packed leaves that form a head, whereas kohlrabi has been selected for its thick aboveground stem (Warwick 2011). In their many forms, brassicas are nutritious vegetables, high in carotenoids, vitamins, calcium, iron, magnesium, and dietary fiber.

Due to their long history of domestication, brassicas also hold deep significance for cultures worldwide. Horseradish, wasabi, and mustard seeds are a few examples of brassicaceous crops used for seasoning and as spices. Collards are tied to the culinary heritage of the African diaspora (Ebony Editorial Staff 2019). In the Southeastern United States (US), collards continue to have cultural significance as a symbol of good luck and prosperity on New Year’s Eve for Black Americans when served with black-eyed peas. Collards are also one of the top 10 vegetables in Southeastern crop production and a recent increase in demand has caused the unit sale price to rise nearly 400% between 2015 and 2019 (USDA ERS 2020). Cabbage is a staple in many Central and Eastern European traditional dishes, shredded and fermented as sauerkraut, as stuffed cabbage rolls, or in various hearty stews (Whats4eats 2023). Cabbage is a treasured vegetable in parts of China as well, symbolizing wealth and prosperity, and even has a traditional folk song named after it (National Garden Bureau 2017). Kimjang, the term for the annual preparation and preservation of kimchi, is typically done in the winter season and is recognized by UNESCO on the Representative List of the Intangible Cultural Heritage of Humanity (Korean Cultural Center NY 2023). This process can include the preparation of several types of kimchi, such as fermented napa cabbage (baechu) and Korean radish (kkakdugi) kimchi. These are just a few of the many ways brassicas play an important role in dishes and customs worldwide.

In the US, the majority of cole crop production occurs in the Western region, primarily due to the more frequent occurrence of optimum production temperatures, reduced disease and pest pressure, and the availability of labor (Rozyne 2022). Cabbage has a nationwide estimated production value of $613 million, with California (CA) historically dominating the market (USDA NASS 2022). CA had a 2022 crop value worth $155 million, whereas New York (NY) was second in production at $74 million (USDA NASS 2023). New Jersey (NJ), another significant producer of specialty crops on the East Coast, had principal vegetable sales valued at $184 million in 2021; this included multiple cole crops, including cabbage (USDA NASS 2022). In 2021, cabbage production in NJ was valued at $7.9 million, with 1400 acres in production (USDA NASS 2022). In 2022, broccoli was voted America's favorite vegetable by 5,000 consumers in The Green Giant brand's annual poll (The Produce News 2022). Broccoli has a higher production value nationwide ($814 million), compared to cabbage, with Arizona (AZ) and

CA being the top in production. According to the 2017 Census of Agriculture, broccoli production in NY totaled 634 acres (USDA 2019).

Cole Crop Production

Cole crops are cool season commodities, with the optimum growing temperatures falling between 15-20 ˚C, although there can be significant differences in performance among crops and varieties (Guerena 2020; Wyenandt et al. 2023). For example, cabbage is typically more heat tolerant than broccoli. Extended periods of low temperatures may cause some cole crops to bolt or button; conversely, extended periods of high temperatures can cause broccoli to remain vegetative. Both extremes can result in marketability concerns for producers. In 2022, pricing of conventional and organic broccoli rose 22% and 67%, respectively, due to severe weather and disease pressure in major production areas such as CA, Florida (FL), and Mexico, which reduced marketable yields and availability of broccoli (Davis et al. 2022). To overcome some of the environmental impacts limiting production and dependence on singular production regions, broccoli breeding efforts to support the establishment of an Eastern US crop have developed and introduced new varieties that can perform under a broader range of temperatures (Farnham and Björkman 2011). Although an Eastern broccoli industry is feasible from a supply-chain perspective, broccoli production in Eastern systems needs to be profitable and the pivot away from existing agricultural production needs to make financial sense (Atallah et al. 2014). The profitability of the Eastern broccoli industry will depend on additional factors such as crop yields of new varieties, labor availability, and the efficacy of pest control, which includes availability of weed control options (Harrison and Farham 2013; Royzne et al. 2021). Currently, weed control options for specialty crops such as cabbage and broccoli are limited.

Losses Due to Weeds

Weeds are a significant threat to cole crop production. With respect to their direct impacts, weeds compete with the brassicas for water, nutrients, and light. Indirect impacts are noteworthy, as well. For example, weeds can also harbor pests and pathogens and may physically impede or delay harvest activities (Bell 1995; Hammerton 1966; Chen et al. 2011). Yield losses due to weeds in cabbage and broccoli can be economically devastating to growers. Averaged over 44 studies across 20 years, conducted mostly in MI, ON, NY, NJ, and WI, there was an estimated yield loss of 54% in cabbage if weeds were not controlled (M. VanGessel, personal communication).

Weed competition studies are complex and may include interacting variables to explain the impact of individual weed species and weed communities on crop performance. Weed density, type of weed, timing of treatments, planting method, and environmental conditions such as temperature and water availability, among other factors, are all important considerations when conducting these types of trials. Some studies model crop-weed competition following the work that Cousens (1987) established in utilizing a rectangular hyperbola model to assess and estimate critical control periods and thresholds for control. These modeling studies typically only account for one weed species in competition with the crop, which is not representative of field conditions. Other weed competition trials simply compare treatment group yields to the hand weeded control group. Across these studies, one thing is consistent: as weed density increases, crop yields decrease.

In field studies conducted in Freeville, NY, Bellinder (2012) reported a 55% yield loss in cabbage when weeds were not controlled, compared to the hand weeded check. Bell (1995) found that an average of 4.9 Italian ryegrass (*Lolium perenne* L.) plants m $^{-2}$ were enough to reach the economic threshold value (3.6%) for broccoli produced in California's Imperial Valley, suggesting that weed densities above those values would cause a yield loss surpassing the cost of post-emergence (POST) weed control; harvest delays were also reported. Miller and Hopen (1991) observed that velvetleaf densities of 3.6 plants m^{-2} reduced cabbage yield up to 92% relative to the weed-free control. Latif et al. (2021) used a linear additive model, developed from two years of field studies, to estimate that with an increase of fresh weed biomass of 1 g m^{-2} there could be a total yield loss of broccoli of 0.0075 t ha^{-1} and a marketable yield loss of 0.003 t ha^{-1}, resulting in an economic loss for growers. Bitterlich (1990) fit yield data to a rectangular hyperbolic model to find that one lambsquarter plant m^{-2} reduced broccoli total yield by 18-20% and marketable yield by 22-37%, while also decreasing the average head weight. Bitterlich (1990) also observed that weed competition was so great that no marketable broccoli heads would be produced when weed density was greater than 8 lambsquarter plants m^{-2}.

Cole crops are short in stature with relatively shallow root systems, making them poor competitors against weeds, highlighting the need for effective weed management tactics (Sikkema et al. 2007; Yu et al. 2018). The incidence of rainfall in the eastern US can facilitate the emergence and rapid growth of weeds, which can put direct-seeded crops at significant risk for failure if successful weed control is not achieved (Cutulle et al. 2019; Harrison and Farham 2013; Sikkema et al. 2007; Myers et al. 2011; Mohler 2021). Consequently, a significant proportion of brassica production in the Eastern US relies on transplants to establish a height differential and provide crops with a competitive advantage against early germinating weeds during the critical period of weed control (Cutulle et al. 2019; Harrison and Farham 2013; Sikkema et al. 2007; Myers et al. 2011; Mohler 2021). The critical control period is defined as the period, usually very early in the crop life cycle, in which weed management is most impactful in preventing yield loss. While the timing of when competitive interactions occur can influence the duration of the critical control period, other factors, such as weed spectrum and density and whether the crops were seeded or transplanted, also play important roles. For example, Miller and Hopen (1991) found that the critical control period in seeded cabbage was 2 weeks in 1988 and 4 weeks in 1989. Differences in the identity of dominant weed species between the two years could explain the observed disparities. Interestingly, Miller and Hopen (1991) did suggest that the emergence of weeds after the critical control period could provide benefits to cabbage plants by reducing thermal stress to the and maintaining soil moisture, which, in turn, minimized yield reductions.

Latif et al. (2021) reported that the critical control period for transplanted broccoli lies between 15 and 30 days after planting. Crop variety, weeding intervals, and the interaction between the two factors resulted in significantly different yields in broccoli with the combination of 'Galabrease' broccoli and weeding at 15 days after transplant producing the highest marketable yields of 11.30 t ha^{-1} to 12.27 t ha^{-1} (Latif et al. 2021). Similarly, Weaver (1984) found that the critical weed control period for transplanted cabbage was between 21 days and 35 after planting; Weaver also reported that other management techniques such as increasing planting density (by decreasing between-plant spacing from 2 m to 0.75 m) also consistently increased yields. Planting densities may shift the critical period of weed control, as weed competition begins sooner with higher planting densities (Weaver 1984).

Weeds can also support populations of pests and pathogens, which can have damaging effects beyond the impacts of direct weed competition. For example, Swede Midge (Diptera: Cecidomyiidae) is a destructive pest for cole crops, causing an estimated $3706 ± 1394 acre per year in damages in NY (Hodgdon et al. 2022). Brassicaceous weeds such as Shepherd's purse (*Capsella bursa-pastoris* L.) and field pennycress (*Thlaspi arvense* L.) can serve as hosts for other insect pests such as cabbage aphid (*Brevicoryne brassicae* L.), cabbage looper (*Trichoplusia ni* (Hübner)), diamondback moth (*Plutella xylostella* L.), cabbage maggot (*Delia radicum* L.), cabbage whitefly (*Aleyrodes proletella* L.), and flea beetles (*Alticini* Newman) (Guerena 2020). Furthermore, weeds in the mustard family can serve as alternate hosts for the pathogens that cause Alternaria leaf spot (*Alternaria brassicae, A. brassicola*), bacterial black rot (*Xanthomonas campestris*), and club root (*Plasmodiophora brassicae*) diseases (Chen et al. 2011; Guerena 2020). Sclerotinia rot (*Sclerotinia sclerotiorum* (Lib.) de Bary) can cause stem rot in both cabbage and broccoli, with serious losses in both the field and postharvest environments. Common ragweed (*Ambrosia artemisiifolia* L.) flowers and seeds, as well as any other infected plant part have been identified as a source of Sclerotinia rot infection for cabbage plants in New York (Dillard and Hunter 1986). Pathogen transmission of clubroot and Sclerotinia rot, as well as others, can be mediated and exacerbated by insect pest damage (Guerena 2020). For this reason, weed management can play a part in reducing disease and pest incidence, therefore reducing crop losses.

Weeds are also a concern with respect to worker safety. Certain weed species can be considered occupational hazards for agricultural workers during harvest. This includes the production of thorns or spines, as with horsenettle (*Solanum carolinense* L.). It can also include the production of photosensitizing substances, such as furanocoumarins by members of the *Apiaceae* family, which result in severe blisters and edema on laborers with exposed skin (Bridges 1994). Weeds can also induce allergic reactions; Common ragweed (*Ambrosia artemisiifolia* L.) is one of the major causes of seasonal allergies in the fall (Ennis 1958). In cole crops where hand weeding is an important method of weed control, human health considerations are critical. Weeds with poisonous or staining berries and those with small seeds can also contaminate harvests resulting in economic losses (McErlich and Boydston 2013). Cabbage and broccoli processing standards require heads of these crops to meet color, size, and compactness requirements, as well as be free from serious damage from insect or disease (USDA AMS 1997a, USDA AMS 1997b). New York's cabbage production is mainly for the processing market. These quality considerations are of utmost importance for farm profitability.

Weed Management

Weed management is a problem for vegetable growers everywhere. According to USDA's Invasive Weed Management Unit, weed control is ranked as the most critical problem facing organic growers. For conventional growers, weeds are also a problem, even though they may have more options for weed control compared to organic producers. Many conventional weed management tactics rely heavily on chemical control methods, predominantly synthetic herbicides, although specialty crop producers still have limited options from which to choose compared to agronomic cropping systems. There are some organic herbicides made from natural ingredients that are approved by the National Organic Program for use in organic production. However, many can be inconsistent with respect to efficacy; they are also more expensive than their conventional counterparts. In some rare instances, when there are no naturally occurring alternatives, synthetic products may be utilized in organic production after a thorough vetting process (Coleman 2012).

The Agricultural Statistics Book (2021) estimates that 43% of broccoli acreage in production receives some type of pesticide application. In the past 40 years, the cost of pesticides has decreased relative to the cost of seed prices, cost and availability of labor, and costs of machinery, making herbicide use a preferred method of weed control (Bridges 1994). Herbicides may be able replace or reduce the use of hand weeding and cultivation for weed control, while simultaneously reducing the cost of control and increasing crop yield (Gianessi and Reigner 2007). This is important because, in general, specialty crop farms have the highest proportion of labor costs as proportion of total cash expenses (MacDonald et al. 2013, Myers et al. 2011). Gianessi and Sankula (2007) reported that herbicide adoption replaced 20 hours per acre of hand weeding in broccoli. The combined cost of non-chemical weed control in 2003, including tillage and hand labor (at $8.75 per hour) in 2001, was calculated to be $184 per acre for broccoli production (Gianessi and Sankula 2003). Growers reported that in the switch from hand labor to herbicide usage for weed control, yields went up by 30% with reported savings of up to $35 per acre. However, these data are more than 20 years old and labor costs have only increased; this includes costs associated with guestworker visa programs.

Despite the use of herbicides, human labor is still critical for suppressing or eliminating unwanted vegetation. There are situations in which herbicides are less effective, such as with severe infestations or when there are instances of herbicide resistance. Sometimes, the available registered products in specialty crops are not adequate for controlling the full spectra of weeds found in a particular production environment. When cole crop and leafy greens growers were surveyed about current weed control tools and practices in 2022, hand weeding came up as the most commonly used practice (M Cutulle, personal communications). When hand weeding is employed, it can come at an incredible cost. If the infestation is particularly extreme, or weed density is high, the cost of hand weeding in cabbage could exceed \$1200 ha^{-1}, which can be above profitable levels (Smart et al. 2001).Amisi (2005) estimated that the cost of labor for hand weeding up to the critical control period of cabbage to be \$192 per hectare, assuming a minimum wage of \$6 per hour. Amisi (2005) also calculated that the labor involved in the no seed threshold approach (i.e., removing weed escapes to prevent seed rain), which involved hand weeding throughout the entire growing season, cost \$296 ha^{-1} in cabbage in Ohio. The cost associated with transplanting brassicas could also be considered a weed control expense as this planting strategy can confer a competitive advantage to the crop.

Weed control efforts, while dominated by herbicides and hand weeding, can also be accomplished by additional strategies/collections of strategies. Some growers employ a method known as integrated weed management (IWM) in their operations. IWM refers to a combination of practices and methods to control weeds, informed by a holistic understanding of weed biology and ecology, without putting importance on one mechanism of control over another (Harker and O'Donovan 2013). This approach to weed management incorporates a combination of chemical, biological, physical, and cultural practices. Increased planting density, cultivation, competitive crop varieties, tillage, and stale seedbed, are all examples of tactics that could be employed in addition to chemical control methods to employ a more integrated weed control program (Mohler et al. 2021). Organic production also relies on a similar hierarchy to devise pest management programs that focus first on prevention, then on biological and physical intervention, and lastly, the use of some chemical products as a last resort (Coleman 2012). Although conventional growers are not bound by the same strict guidelines that organic growers may be, some will choose to adopt IWM practices to reduce reliance solely on chemical control options.

The use of herbicide treatments, especially when in combination with other methods of weed control, can be a low-cost way to increase yields, reduce seed rain, and reduce labor costs. Cutulle et al. (2021) found that cultivation, in addition to herbicide treatments, generally resulted in enhanced weed control and better yields in broccoli such as increased stem diameter and head weights. Cultivation may help crop performance due to increased aeration proximal to the roots, in addition to removing weeds. Akshatha et al. (2018) found that other weed control treatments that combined chemical and non-chemical approaches helped to increase yields, such as the use of plastic mulch, the application of PRE herbicides plus hand weeding, and a stale seedbed combined with a burndown herbicide. Integrated weed management also focuses on reducing or preventing the return of viable weed seed to the soil seedbank. Managing the size and composition of the soil seedbank is crucial for improving weed control success across seasons. For example, Miller and Hopen (1991) found that velvetleaf seed capsule production was correlated with its biomass; if the weed was controlled up to 6 weeks after cabbage emergence and destroyed after cabbage harvest, seed production was able to be prevented. Weed seeds can persist in deep soil environments for longer when the conditions are moist and cool, much like the soils in the eastern part of the US (Villiers and Edgecombe 1975). This suggests that seedbank management may be of special importance for Eastern cole crop producers, resulting in increased labor requirements to prevent contributions to the seedbank. By keeping these considerations in mind, growers can develop an effective weed control program for their operation, utilizing chemical and non-chemical control options IWM allows growers to use the most effective management practices in combination with chemical control to most effectively control weeds.

Regulatory Registration and Environmental Considerations

Herbicide active ingredient discovery and commercialization has slowed in recent decades, with the greatest progress found in products for large acreage agronomic crops (Duke 2012). The Interregional Research Project Number 4 (IR-4) is a publicly-funded program that generates data required by the United States Environmental Protection Agency (EPA) to register pest control products for specialty crop growers or minor uses (Kunkel et al. 2008). Broccoli and cabbage are two commodities which are both specialty crops and minor use crops. However, the process to register a product in a specific crop is time consuming, costly, and requires sufficient crop injury and product efficacy data. Data development required for a major agricultural chemical may cost $10 million or more (Culleen 1994). Although nearly all the products being used in specialty crops were originally selected and developed for use in agronomic crops such as cotton, soy, or corn, researchers have found creative solutions that reduce crop injury in specialty crops (Kunkel et al. 2008). For example, researchers found that altering herbicide application methods or timing of product application as outlined on the label intended for agronomic crops have been successful in reducing injury in more sensitive crops such as specialty crops.

As part of the product registration process with the EPA, efficacy and crop injury studies in addition to environmental and human risk assessments need to be conducted. The data required for this product registration process is analyzed by EPA in order to make regulatory and risk management decisions. This authority is granted to the EPA by two major US statutes: the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) and the Federal Food, Drug, and Cosmetic Act (FFDCA). These laws have been amended by the Food Quality Protection Act (FQPA) and the Pesticide Registration Improvement Act (PRIA).

Herbicides have specific use recommendations, with soil environment, temperature and moisture conditions, and many other factors often times influencing injury potential (Anonymous 2020). For example, Harrison and Peterson (1999) observed a temperature effect in increasing oxyfluorfen injury when applied POST in cole crops. They recommended lowering the rate applied when cooler conditions are expected, although the specific mechanism for differential herbicide tolerance depending on temperature is not well known. However, decreasing herbicide rate can also reduce herbicide efficacy. The specific mechanisms of absorption, coupled with application method of the herbicide can influence these crop injury considerations. Since sulfentrazone (which is the focus of chapter 2) is absorbed through the roots, there is concern with direct seeded crops and those with sensitivity to the chemistry (Rachuy and Fennimore 2021). Smart et al. found that successive POST applications (90, 140, and 187 g ai h^{-1}) of sulfentrazone at 2-4 leaf stage in direct-seeded cabbage caused greater incidence of injury compared to single applications at rates ranging from 23 - 187 g ai h^{-1} (2001). These rates of sulfentrazone caused significant injury which was transient and did not negatively impact yield of cabbage. Ferrell et al. (2003) found that localized differences in soil pH could also be responsible for greater sulfentrazone uptake and could explain the unpredictable patterns of injury that have been observed (Niekamp et al. 1999). The potential for crop injury due to sulfentrazone is greater in high pH soils, under cooler weather and in soils with prolonged and excessive moisture (Niekamp et al., 1999; Senseman 2007). There are limited published studies evaluating sulfentrazone for crop safety in specialty crops such as cabbage and broccoli. These types of studies can contribute to the necessary data for product registration in specialty crops.

Specialty crops as defined under Section 101 of the Specialty Crops Competitiveness Act of 2004 (7 U.S.C. 1621 note), amended under section 10010 of the Agricultural Act of 2014, Public Law 113-79 (the Farm Bill) are “fruits and vegetables, tree nuts, dried fruits and horticulture and nursery crops, including floriculture.” Cabbage and broccoli are not only are specialty crops, but, because they are also grown on less than 300,000 acres in the US per year, they are also considered minor use crops. Since these crops are grown on such small acreage, there is may be little economic incentive for agrochemical companies to register new chemical products for pest and weed management. Registering a chemical product is a very expensive, and often lengthy, process, and registrants may have reservations due to product liability concerns with these high value crops (Kunkel et al. 2008). State-by-state differences in additional regulatory requirements (e.g., beyond the federal requirements for product registration), can also limit herbicide availability. Recent herbicide safety and efficacy research in cabbage and broccoli has been conducted in these states by Cornell and Rutgers University researchers to try and increase product availability and ensure safe use in both states. This work will be discussed in greater detail in Chapter 2.

Once products have been made available for use, growers may have concerns about their discontinuation (Grey et al. 2007). Since the 1980's, various chemical control methods used in specialty crops have been removed from the market (Fennimore and Doohan 2008). For example, methyl bromide (MBr), an agricultural fumigant, has been undergoing a phaseout of production or imports starting January 1, 1996, due to its status as a "Class 1" ozone-depleting substance, with exemptions for critical or quarantine and reshipment uses. On April 28, 2022, US Environmental Protection Agency (EPA) issued a notice of intent to suspend the herbicide dimethyl tetrachloroterephthalate (DCPA). In the case of DCPA, the registrant was noncompliant with testing required for continued registration of the product as part of FIFRA. FIFRA is the federal statute that governs the registration, distribution, sale, and use of pesticides in the US.

The EPA also has an obligation to comply with the Endangered Species Act (ESA), which protects species that are threatened with extinction and promotes the recovery of these species. The ESA requires that no action authorized by the EPA, such as the registration of an herbicide, jeopardizes the existence of endangered species nor "destroy or adversely modify" any designated critical habitat. The EPA's newly released roadmap describes the agency's proposed efforts to meet their statutory requirements. With the discovery of per- and polyfluoroalkyl substances (PFAS), also known as "forever chemicals", in agricultural pesticide residues, multiple states and advocacy groups are raising concerns and pushing for EPA to remove certain products from the market until more is known about contamination mitigation. Added hurdles could ultimately affect the use and availability of many herbicides going forward.

Herbicide adoption initially reduced grower dependence on hand weeding and cultivation to control weeds, saving money in the process. However, if important chemistries are removed from the market, crop yields and quality may decrease if there are no suitable alternatives. This could also push growers to revert to or increase their dependence on mechanical control and/or hand labor, which are severely impacted by rising operation costs and labor demand. With a decreased labor pool, and limited access to effective chemistries that do not have negative environmental impacts or cause crop injury, many growers may not be able to effectively control weeds. Not being able to control weeds could also contribute to weed pressure in future years via an increase in the size of the seedbank. All of this in combination can contribute to an increase in cabbage and broccoli prices, as well as a dependence on food imports. For these reasons, development of labor-saving novel weed control technology in specialty crops is an urgent need. Without affordable, practical, and effective weed control options, cole crop production, availability, and price will be impacted as well as consumer access to the nutrients they provide.

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Chapter 2: Crop Safety and Efficacy of Sulfentrazone in Cabbage and Broccoli in New York and New Jersey

Abstract

In 2021 and 2022, research was initiated to evaluate the efficacy and safety of sulfentrazone in transplanted cabbage and broccoli. Treatments included oxyfluorfen 560 g ai ha^{-1} pre-transplant (PRE-T), sulfentrazone 116 g ai ha^{-1} (sulfentrazone low) and 233 g ai ha^{-1} PRE-T (sulfentrazone high), and *S*-metolachlor 715 g ai ha^{-1} immediately applied after transplanting (POST-T) followed by (fb) oxyfluorfen 210 g ai ha^{-1} postemergence (POST) 14 d after planting (DAP). With respect to weed cover, the weedy non-treated plots averaged between 6% (14 DAP) and 72% (42 DAP); all herbicide treated plots averaged less than 30% cover at 42 DAP. At 14 and 28 DAP, the oxyfluorfen, *S*-metolachlor fb oxyfluorfen, and sulfentrazone high treatments reduced total monocot and dicot weed densities (m^{-2}) between 62 and 100%, relative to the non-treated check; hairy galinsoga (NJ) and combined ladysthumb and prostrate knotweed (smartweed) (NY) density was reduced between 71 to 99%. Except for sulfentrazone low, all herbicide treatments reduced weed biomass at harvest by 88% or more. Crop injury varied in response to herbicide treatments or weed competition, but was also affected by crop and location. Between 14 and 28 DAP, the greatest amount of stunting (22%) was observed in the *S*-metolachlor fb oxyfluorfen treatments for both locations. Averaged over herbicides, greater stunting was observed in broccoli as compared to cabbage in NY, whereas stunting estimates were higher for cabbage in NJ. All herbicide treatments applied in NJ significantly increased cabbage yield and broccoli and cabbage head sizes relative to the non-treated check. Differences among herbicide treatments and the non-treated check, with respect to crop yields, were not observed in NY. Data

derived from these studies will be used to enhance crop safety recommendations in Northeast production environments for sulfentrazone use in transplanted cabbage and support a potential label for broccoli.

Introduction:

Cole crops, such as cabbage and broccoli, are important horticultural commodities in the US. In 2022, cabbage was grown on 23,000 ha nationwide, with an estimated value of $613 million (USDA NASS 2023). In 2022, NY ranked second behind CA with respect to area harvested (4,300 ha), yield (192,000 metric tons), and value of utilized production ($74 million) (USDA NASS 2023). Vegetable production in NJ, where annual sales totaled $184 million in 2021, includes multiple cole crops, including cabbage, which was valued at $8 million (USDA NASS 2022). Broccoli is valued at $815 million in the US, with most of the production located in CA and AZ (USDA NASS 2023). The advancement of a broccoli industry in NY and other eastern states has been supported by breeding efforts to develop varieties that are more tolerant of regional growing conditions (USDA 2019; Farnham and Björkman 2011; Wyenandt et al. 2023). Additional factors, such as effective weed management strategies, are also required to maximize yields in broccoli, as well as in other cole crops.

Cole crops are short in stature, with relatively shallow root systems, making them poor competitors with weeds for limited resources (Sikkema et al. 2007; Yu et al. 2018). Direct interference for water, nutrients, and light can reduce both head numbers and size. For example, Bellinder (2012) found that weed interference in cabbage could reduce yields by approximately 55%. In an economic threshold study conducted by Bell (1995), an Italian ryegrass (*Lolium perenne* L.) density of 4.9 plants m^{-2} reduced broccoli yields by 3.6%, resulting in an economic loss equal to the cost of POST weed control ($221 ha^{-1}). Averaged over 44 studies (mostly conducted in MI, NY, NJ, WI, and Ontario) across 20 years, cabbage yield loss was estimated at 54% when weeds were not controlled, despite the use of other best crop production practices (e.g., fertilization, irrigation, insect and disease management) (M. VanGessel, personal communication). Weeds can also impede and delay harvest operations (Bell 1995; Smart et al. 2001; Fennimore et al. 2010). Additionally, some weed seeds can physically contaminate cabbage heads while common ragweed (*Ambrosia artemisiifolia* L.) seeds have the potential to spread the pathogen responsible for Sclerotinia rot (*Sclerotinia sclerotiorum* (Lib.) de Bary) (Dillard and Hunter 1986). Furthermore, weeds of the mustard family, such as shepherd's purse (*Capsella bursa-pastoris* L.) and field pennycress *(Thlaspi arvense* L.) can serve as alternate hosts for the pathogens that cause Alternaria leaf spot (*Alternaria brassicicola* (Schweinitz) Wiltshire), bacterial black rot (*Xanthomonas campestris* (Pammel) Dowson), and club root (*Plasmodiophora brassicae* Voronin) diseases (Chen et al. 2011; Guerena 2020). Seed contamination and disease stress can reduce cabbage and broccoli head quality, potentially decreasing yields and increasing the labor required to achieve industry standards for fresh or processing markets.

Herbicides are important tools for the management of weeds in cabbage and broccoli production systems, although the effectiveness of chemical weed control is limited by the relatively few numbers of registered products and their narrow spectrums of control (Sikkema et al. 2007; Wyenandt et al. 2023). Sulfentrazone is an aryl triazinone herbicide that inhibits the protoporphyrinogen oxidase (PPO) enzyme (Weed Science Society of America Group 14) and for which use in cole crops is limited to transplanted cabbage in some states (including NJ but not NY). It can be used preemergence (PRE), early preplant, or preplant incorporated with targeted activity against many annual broadleaf weed species including pigweeds (*Amaranthus* spp.), common lambsquarters (*Chenopodium album* L.), some morningglory species (*Ipomoea* spp.), and some annual grasses, such as foxtails (*Setaria* spp.) and witchgrass (*Panicum capillare* L.) (Hartzler 2004; Niekamp 1998; Niekamp et al. 1999; Taylor-Lovell et al. 2001; Senseman

2007). Yellow nutsedge (*Cyperus esculentus* L.) suppression can be achieved by applying sulfentrazone PRE or POST at 420 g ai ha^{-1}, which is the maximum allowable rate per season (Anonymous 2022). Sulfentrazone has also demonstrated suppressive activity against field bindweed (*Convolvulus arvensis* L.) (LM Sosnoskie, unpublished data). Several states have a special local needs label for sulfentrazone to be used in various specialty crops for control of broadleaved weeds, sedges and haircap moss (*Polytrichum commune* Hedw.).

Regarding crop safety, sulfentrazone applied PRE can be inconsistent with respect to observed crop damage incidence and severity, largely due to underlying edaphic conditions (Niekamp et al. 1999; Vencill 2002). For example, Ferrell et al. concluded that variability in soil pH within site could differentially affect sulfentrazone uptake and resulting injury patterns (2003). Especially in soils with pH near 6.5, sulfentrazone-soil dynamics are particularly variable, with organic matter and soil type also playing a major role (Grey et al. 1997; Anonymous 2022). The Northeastern and Mid-Atlantic regions of the United States have a high average rainfall, which could impact sulfentrazone uptake, leaching below root level, and microbial degradation, all of which can influence weed control efficacy and crop injury potential (Senseman, 2007; Mueller et al. 2014). These regions are also home to a diversity of agricultural soil types, all with different properties such as pH and organic matter content, which have implications on crop-herbicide dynamics as well.

As consumer demand for local foods increases, the need for effective weed control options in vegetable production near eastern US population centers is imperative (Atallah et al. 2014). There are few studies evaluating weed control and cabbage and broccoli tolerance to sulfentrazone applied PRE-T, particularly under Northeast environmental conditions. The objectives of this research were to evaluate weed control and cabbage and broccoli tolerance to sulfentrazone to support recommendations regarding the safe and effective use of this active ingredient.

Materials and Methods

Site description. In 2021 and 2022, experiments to evaluate weed control efficacy and crop safety of sulfentrazone in cabbage and broccoli were conducted at Cornell AgriTech in Geneva, NY (42.87032° N, 77.02728° W) and at the Rutgers Agricultural Research and Extension Center in Bridgeton, NJ (39.523611°N, 75.201944°W). Soil in Geneva was a Honeoye loam (fine-loamy, mixed, semiactive, mesic Glossic Hapludalfs) with 38% sand, 44% silt, 18% clay, 2.5% organic matter, and a pH of 6.3. The Bridgeton site was a Chillum silt loam soil (fine-silty, mixed, semiactive, mesic Typic Hapludults) with 54% sand, 28% silt, 18% clay, 2.4% organic matter content, and a pH of 5.7.

Plot size and plant material. All fields were disked prior to transplanting to eliminate emerged weeds. In Geneva, plots were 7.6 m in length and 3.1 m in width. Each plot had two rows of broccoli next to two rows of cabbage on 76.2 cm spacing; individual plant spacing within rows was 50.8 cm. Cabbage (var. ‘Padoc’) and broccoli (var. ‘Emerald Crown’) were transplanted into flat beds on May 20, 2021, and May 10, 2022. In Bridgeton, plots were 9.1 m in length and 3.1 m in width. Each plot had two rows of broccoli next to two rows of cabbage on 76.2 cm spacing; individual plant spacing within rows was 30.5 cm. Cabbage (var. ‘Botran’) and broccoli (var. ‘Avenger’) were transplanted on August 17, 2021, and cabbage (var. ‘Padoc’) and broccoli (var. ‘Emerald Crown’) were transplanted on August 4, 2022. All transplants had three to four leaves at planting; root balls were placed at least 5 cm deep at both locations. Both sites received 1.5 cm supplemental irrigation on the same day as planting to set transplants and incorporate soil-applied herbicides. Additional irrigation was supplied as needed in NJ while the NY site was rainfed. Both sites followed local pest and crop management guidelines with respect to fertilization and insect and disease control.

Treatments. The experiment was arranged as a split plot design with four replications; herbicide treatments were considered as the main plot and cole crop species as the subplot. Herbicide treatments included oxyfluorfen (GoalTender®; Nufarm Inc., Alsip, IL) at 560 g ai ha^{-1} PRE-T (hereafter referred to as 'oxyfluorfen'), sulfentrazone (Spartan Charge® in NY and Zeus® XC in NJ; FMC Corp., Philadelphia, PA) at 116 ai ha^{-1} or 233 g ai ha^{-1} PRE-T , and *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Greensboro, NC) at 715 g ai ha^{-1} applied POST-T fb oxyfluorfen at 210 g ai ha^{-1} applied 14 DAP (hereafter referred to as '*S*-metolachlor fb oxyfluorfen'). Selected rates reflect label recommendations regarding soil texture and organic matter content. A non-treated weedy control was also included for comparison.

In NY, herbicide treatments were applied using a CO_2 backpack sprayer and a 2-nozzle boom equipped with XR11002VS nozzles (TeeJet Technologies, Glendale Heights, IL) set 48 cm apart, and calibrated to deliver 187 L ha^{-1} at a pressure of 276 kPa. In NJ, herbicides were applied using a CO_2 backpack sprayer and a 4-nozzle boom equipped with XR8004VS nozzles (TeeJet Technologies, Glendale Heights, IL) nozzles, each set 46 cm apart and calibrated to deliver 187 L ha^{-1} at a pressure of 207 kPa.

Data collection. Crop injury was visually estimated using a scale ranging from 0% (no visible injury) to 100% (total plant death). Across both years, sites, and crops, the predominant injury response was stunting, although minor chlorosis and necrosis was also observed. Visible injury for both cabbage and broccoli was assessed at 14, 21, 28, and 42 DAP. Weed cover, a visual estimate of the percentage of plot area covered with weeds, was evaluated both years in NY and in 2022 in NJ at 14, 21, 28, and 42 DAP using a scale of ranging from 0% (no weed cover) to

100% (soil completely covered by weeds). At 14 and 28 DAP, individual weed plants were separated by species and counted in a 0.25 m^2 quadrat positioned in the direct center of each cabbage and broccoli subplot in each herbicide treatment whole plot. At crop harvest, aboveground weed biomass was collected from two 0.25 m^2 quadrats placed in the center of each crop subplot.

In 2021, NY cabbage and broccoli harvests occurred ahead of schedule on July 21 (63 DAP) due to significant rainfall and soil waterlogging, which resulted in crop vigor loss and disease development (Table 1). In 2022, exceptionally dry conditions occurred during head development necessitating an early harvest on July 13 (65 DAP). In 2021, mean head weight per plot was determined by averaging the data from 10 heads harvested from adjacent rows of cabbage and broccoli in each plot. In 2022, all heads in each row of cabbage and broccoli were harvested to produce a mean per head weight. In NJ, broccoli and cabbage harvest occurred on October 28 in 2021 (72 DAP) and October 6 in 2022 (63 DAP). Both years, mean head weight and circumference were computed by averaging weight and equatorial circumference of 10 heads collected from both rows within the center of each plot.

Statistical Analysis. Because of unequal variances, weed cover and crop injury data were arcsine square root transformed prior to analysis and back transformed for presentation of the data (Grafen and Hails 2002). Data were subjected to ANOVA using PROC GLIMMIX in SAS version 9.4 (SAS Institute Inc., Cary, NC) to evaluate the impacts of residual herbicide applications, cole crop species, and their interaction on visual estimate of weed cover and crop injury, weed count and aboveground biomass, and crop yield and head circumference. Location, cole crop species, and herbicide treatments were considered fixed effects whereas year and replications nested within year were treated as random effects. In the case where an interaction including location was significant, data were separately analyzed by location. In the absence of significant residual herbicide treatment by crop species interactions, data were combined over fixed effects and mean comparisons between treatments were performed using Tukey's honest significance test at (α= 0.05.)

Results and Discussion

Weed cover. Both trial locations were planted in fields with substantial weed pressure. Dominant species at the Geneva site included common ragweed, ladysthumb (*Polygonum persicaria* L.), prostrate knotweed (*Polygonum aviculare* L.), shepherd's purse, field pennycress, common lambsquarters, and annual grasses including foxtails and barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.]. Dominant species at the Bridgeton site included hairy galinsoga (*Galinsoga quadriradiata* Cav.), yellow nutsedge, common lambsquarters and oakleaf goosefoot (*Chenopodium glaucum* L.), carpetweed (*Mollugo verticillata* L.), redroot pigweed (*Amaranthus retroflexus* L.), and annual grasses including stinkgrass [*Eragrostis cilianensis* (All.) Vignolo ex Janch.] and goosegrass [*Eleusine indica* (L.) Gaertn.].

Results from ANOVA indicated significant effects ($P<0.0001$) of crop (21 and 42 DAP) and the interaction between crop and herbicide (42 DAP) with respect to total weed cover (Table 2). However, herbicide was the predominant factor influencing the amounts of weedy vegetation observed in the trials (Table 2). Averaged across locations, all herbicide treatments reduced mean total weed cover, relative to the non-treated check, for each observation date. Furthermore, the oxyfluorfen, *S*-metolachlor fb oxyfluorfen, and sulfentrazone high treatments did not differ from each other at 14, 21, and 28 DAP. At 42 DAP, the sulfentrazone low (27%) and high (21%) treatments had higher weed cover estimates than the oxyfluorfen (2%) and *S*-metolachlor fb oxyfluorfen (1%) treatments and lower weed cover estimates relative to the non-treated check (72%).

Weed density. Hairy galinsoga (NJ), smartweeds (NY), and common ragweed (NY) were selected for individual analyses because they were recurrent across treatments and years within their respective locations (Table 3). In NJ, hairy galinsoga densities were affected ($P<0.0001$) by herbicide treatment. At 14 DAP, oxyfluorfen (1 plant m^{-2}) and *S*-metolachlor fb oxyfluorfen (3 plants m^{-2}) reduced hairy galinsoga densities compared to the non-treated controls (70 plants m^{-2}). At 28 DAP, hairy galinsoga densities were 1 plant m^{-2} in both the oxyfluorfen and *S*-metolachlor fb oxyfluorfen treatments, which were lower than the non-treated check (29 plants m^{-2}). The sulfentrazone high treatment also reduced hairy galinsoga densities at 14 (7 plants m^{-2}) and 28 (11 plants m^{-2}) DAP, relative to the non-treated check, although not as well as the two non-sulfentrazone treatments. The low rate of sulfentrazone did not differ from the non-treated check with respect to hairy galinsoga suppression.

In NY, smartweed and common ragweed numbers were also affected ($P<0.0001$) by herbicide treatment. At 14 DAP, oxyfluorfen (1 plant m^{-2}) and *S*-metolachlor fb oxyfluorfen (0 plants m^{-2}) reduced smartweed densities compared to the non-treated control (7 plants m^{-2}); at 28 DAP, smartweed densities remained at 1 and 0 plants m^{-2} in the oxyfluorfen and *S*-metolachlor fb oxyfluorfen treatments, respectively, compared to the non-treated check (21 plants m^{-2}). The sulfentrazone high treatment also reduced hairy galinsoga numbers at 14 and 28 (2 plants m^{-2}) DAP, relative to the non-treated check. The low rate of sulfentrazone did not differ from the non-treated check with respect to smartweed suppression. Common ragweed densities were lower compared to hairy galinsoga and smartweed and were not affected by any herbicide treatment at 14 DAP except for *S*-metolachlor fb oxyfluorfen. At 28 DAP, oxyfluorfen (1 plant m^{-2}) and *S*-

metolachlor fb oxyfluorfen (0 plants m^{-2}) were the only treatments that reduced common ragweed numbers relative to the non-treated control (9 plants m^{-2}).

All herbicide treatments reduced ($P<0.0001$) total monocot and dicot weed densities compared to the non-treated control at both 14 and 28 DAP; the one exception was the sulfentrazone low treatment at 28 DAP (37 plants m^{-2}), which did not improve dicot control relative to the check (65 plants m^{-2}) (Table 4). Except for monocots at 14 DAP, differences ($P\leq0.05$) in total monocot and dicot weed densities were also detected between locations; NJ consistently had higher weed counts across all treatments than NY.

Weed biomass. At harvest, weed biomass was the lowest in the oxyfluorfen and *S*-metolachlor fb oxyfluorfen treatments with 9 and 4 g m^{-2}, respectively (Table 4). The sulfentrazone high treatment was less effective than oxyfluorfen and the *S*-metolachlor fb oxyfluorfen treatments at reducing weed biomass (67 g m^{-2}) but performed better than the non-treated control (575 g m^{-2}). The sulfentrazone low treatment (232 g m^{-2}) did not differ with respect to weed biomass accumulation from both the sulfentrazone high and weedy check treatments. Weed biomass was double in NJ compared to NY. This was most likely due to environmental conditions experienced during both trial years. For example, in 2022, the rainfed NY trial site experienced lower than average rainfall that could have suppressed weed emergence and growth (Table 1).

Another factor that may have played a part in the biomass differences between sites is the biology of hairy galinsoga, one of the major weeds in NJ that was not present in NY. Hairy galinsoga has no seed dormancy, which allows it to continuously germinate and contribute seed to the seedbank throughout the growing season (Brown et al. 2022). As such, hairy galinsoga contributed a disproportionately high amount to the total weed biomass in NJ, combining with the environmental and irrigation differences between the sites to double the biomass. The differences in weed spectra between the two sites, along with their emergence peaks, also may have compounded the above effects. For example, both Palmer amaranth and hairy galinsoga have a delayed emergence peak compared to other summer annuals (Brown et al. 2022). When combined with the effects of differing residual activity between the herbicides, also impacted by environmental and edaphic conditions, we observed weed biomass differences between the sulfentrazone treatments compared to the non-sulfentrazone treatments across sites.

Cole crops are not very competitive against weeds due to their stature, shallow root systems, and slow canopy closure (Sikkema et al. 2007; Yu et al. 2018). Early season control of weeds in transplanted cabbage (21-35 DAP) and broccoli (15-30 DAP) is critical to maintain vigor and yield of the crop (Latif et al. 2021; Weaver 1984). Oxyfluorfen and *S*-metolachlor are commonly used herbicides in cabbage and other cole crops. The efficacy and safety of these ingredients can vary according to weed spectrum, rate, combination with other products, and timing of application.

Sulfentrazone applied POST has shown varied, but generally successful, broadleaf weed control in cole crop production in different environments. In Arizona, Umeda et al. (1999) observed some silversheath knotweed (*Polygonum argyrocoleon* Steud. ex Kunze) control at 3 and 5 weeks after treatment (WAT) (82 and 78%) in cabbage and broccoli with sulfentrazone applied POST at 560 g ai ha^{-1}. Silversheath knotweed control decreased to 64% (3 and 5 WAT) when applied at 280 g ai ha^{-1} and to 68% (3 WAT) and 57% (5 WAT) at 140 g ai ha^{-1}. London rocket (*Sisymbrium irio* L.) and annual sowthistle (*Sonchus oleraceus* L.) control closely followed the patterns observed with silversheath knotweed and was similarly reduced by decreasing rates of sulfentrazone. In less arid South Texas, Smart et al. (2003) found more successful control of broadleaved weeds such as crownbeard [*Verbesina encelioides* (Cav.) Benth. & Hook. f. ex A. Gray] and Palmer amaranth (*Amaranthus palmeri* S. Wattson) with POST applications of sulfentrazone in cabbage. Rates of sulfentrazone ranged from 23 g ai ha^{-1}and 187 g ai ha^{-1} and controlled crownbeard (90-99%) and Palmer amaranth (94-99%).

Other weed control studies with sulfentrazone have been in soybean when applied PRE. Walsh et al. (2015) found 90% reduction of dry weight at 9 WAT of redroot pigweed, common ragweed, common lambsquarters, and green foxtail in soybean calculated from dose response curves at rates of 214, 514, 133, and 721 g a.i. ha^{-1}, respectively. The results from our study similarly reflected that there were differences in sulfentrazone weed control between broadleaf weed species. These studies in cole crops and soybean also support that sulfentrazone may be an effective addition to existing weed control programs that could help broaden the spectrum of weeds controlled.

Crop injury. The crop injury data have been separated by state because site by herbicide and site by crop interactions were significant for each rating date. In NY, significant differences ($P<0.0001$) were observed among herbicide treatments with respect to crop stunting at 14, 21, and 28 DAP (Table 5). The greatest amount of injury at 14, 21, and 28 DAP occurred in the sulfentrazone high (9 to 15%) and *S*-metolachlor fb oxyfluorfen (4 to 22%) treatments. The sulfentrazone low and oxyfluorfen treatments had injury rating estimates of 5% or less at all observation dates. Injury was transient and almost unobservable by 42 DAP. No injury was observed in the non-treated checks at any time. There was a difference ($P<0.0001$) in the amount of stunting observed between crops in NY in the three weeks after transplanting; broccoli experienced 4 and 2 times the crop injury observed in cabbage at 14 and 21 DAP, respectively (Table 5).

In NJ, there were no significant differences among herbicide treatments with respect to crop injury at 14 and 28 DAP (Table 6). At 21 DAP, *S*-metolachlor fb oxyfluorfen had 22% stunting, which was higher (P=0.0002) than all other treatments and the non-treated control. The severe stunting observed in broccoli (61%) and cabbage (70%) in the non-treated checks at 42 DAP was likely the result of intense weed competition (Table 6). At 42 DAP, stunting observed in the sulfentrazone low (10% broccoli, 26% cabbage) and high (10% broccoli, 19% cabbage) was also likely related to weed competition. When averaged over herbicide treatments, greater injury was observed in cabbage as compared to broccoli at 14 DAP (5 vs 0%, P<0.0001), 21 DAP (7 vs 3%, P=0.0007), and 28 DAP (1 vs 0%, P=0.0195).

Rachuy and Fennimore (2022) reported that transplanted brassica vegetables were tolerant to PRE applied *S*-metolachlor and sulfentrazone, up to rates of 730 and 110 g ai ha^{-1}, respectively. There was little to no visible crop injury and no reduction in yield observed in transplanted brussels sprouts (*Brassica oleracea* L. var. *gemmifera* DC) and kale (*Brassica oleracea* L. var. *palmifolia)*. Similarly, Sikkema et al. (2007) did not observe significant crop injury nor reduction in head size nor yield from oxyfluorfen (560 and 1120 g ai ha^{-1}) or sulfentrazone (100 and 200 g ai ha^{-1}) applied PRE in transplanted broccoli, cabbage, and cauliflower *(Brassica oleracea* L. var. *botrytis).* Sikkema et al. hypothesized that transplanted cole crops' root systems are separated spatially from the herbicide-treated zone, therefore reducing injury observed.

Higher crop injury has been observed in some cases when sulfentrazone treatments were applied POST, although results are variable. Seeded broccoli was tolerant to sulfentrazone applied PRE post-planting at 168 g ai ha^{-1} but at 280 g ai ha $^{-1}$ the injury was significant and reduced crop yields, suggesting that this crop has a narrow window of tolerance for sulfentrazone (Haar et al. 2002). Sulfentrazone is a weak acid (pKa= 6.56), which especially impacts soil-herbicide dynamics when the soil pH is near the pKa (Grey et al. 1997). In our study, the soil pH was 6.3 in NY and was 5.7 in NJ. Higher soil pH will increase root absorption of sulfentrazone, which may explain inconsistencies in study results with PRE applied sulfentrazone in sites with different soil pH and moisture levels (Ferrell et al. 2003; Senseman 2007; Vencill 2002). Umeda et al. (1999) found that cabbage was more sensitive than broccoli regarding sulfentrazone injury when applied at rates of 140 and 280 g ai ha^{-1}. These patterns observed were similar to the findings in NJ but not NY in our study. However, their study reported severe injury in sulfentrazone applied POST to cabbage, with marginally acceptable injury observed in broccoli (15%). The injury observed in cabbage and broccoli by Umeda et al. (1999) was higher than the average injury observed by any of the sulfentrazone rates in our study, averaged across crops, except for sulfentrazone high in broccoli at 28 DAP in NY, which was also 15%. Similarly, Smart et al. (2001) observed sulfentrazone injury in seeded cabbage when applied POST at rates of 23, 46, 93, 140, and 187 g ai ha^{-1}, with substantial injury observed above 93 g ai ha^{-1}. However, cabbage head weight, circumference, and weight were only reduced by the highest rate. These results align with what was observed in our study, which demonstrates that long-season cole crops, under good growing conditions, have the potential to outgrow herbicide-related crop injury up to 22%.

Differences observed between published sulfentrazone studies and the results from our study highlight the injury potential related to application timing in cabbage and broccoli, with differences by crop and location. Harrison and Peterson (1999) found that cultivar and temperature responses were related to observed crop injury in broccoli for PRE applied oxyfluorfen, whereas collards and broccoli were observed to have differential injury responses to POST applied oxyfluorfen that varied by temperature and cultivar. In addition to the differences between the environmental and edaphic conditions in our NY compared to NJ sites, cultivar considerations and planting date may explain the crop injury variations observed by location.

Bellinder et al. (1989) observed the impact that application timing had on two cabbage varieties in two NY locations receiving metolachlor PRE (1700, 2200, 4400 g ai ha^{-1}) and 48-hours POST (1700, 2200, 4400 g ai ha^{-1}), with POST improving crop tolerance to this ingredient. There were significant differences between injury responses between the central NY location as compared to coastal Long Island trial sites, highlighting the importance of evaluating crop injury and efficacy in a variety of environmental and edaphic conditions in combination with application timing. Results from Umeda et al. (1999) demonstrate that the range between sufficient weed control and crop tolerance for sulfentrazone applied POST, especially for cabbage, may be small. Our study similarly reflected the rate differences in success of weed control when sulfentrazone was applied PRE, however, crop tolerance did not vary substantially between sulfentrazone rates at either site. Even though in our study, *S*-metolachlor fb oxyfluorfen treatments observed some of the highest crop injury ratings with complete crop recovery, unacceptably high crop injury due to this combination are possible (Bellinder 2012).

Yield. Crop yield data was also separated between locations due to significant location by herbicide interactions. In NY, there was no significant difference among treatment yields (Table 7). This result was likely due to the weather-related stressors that occurred during head development for both years of the study resulting in premature harvests. Harvest in 2021 occurred ahead of schedule due to increased disease and pest pressure related to above average rainfall in July following below average rainfall in June (Table 1). In 2022, Geneva received less than half the 30-year average rainfall for May to November and supplemental irrigation was unavailable. Broccoli is particularly sensitive to heat stressors during the three weeks prior to harvest in Northeastern weather conditions and may have been particularly impacted by a dry 2022 summer (Heather et al. 1992). Additionally, varietal differences in temperature or moisture stress tolerance, as well as structural differences may have influenced the head weights and circumferences, particularly in broccoli. For example, ‘Emerald Crown’ may be best for bunch production rather than crown, depending on the planting timing, and is not recommended for production during rainy seasons (Björkman nd, Anonymous 2019). Field trials conducted in Western NY and Long Island have reported mixed results with an early planting date for ‘Emerald Crown’, with a recommended planting in mid-summer. In trials conducted in Western PA, ‘Avenger’ had, on average, higher head weight than ‘Emerald Crown’ when planted in the fall (Sánchez et al. 2014; Anonymous 2019). These interactive factors may have impacted observed site differences in our study.

Crop head weights ($P<0.0001$) and circumferences ($P=0.0162$) were affected by the interaction between crop and herbicide in NJ (Table 7). Cabbage head weights more than doubled in response to herbicides, compared to the control, and head circumference increased between 12 and 23 cm. Broccoli head circumference increased, by a minimum of 6 cm, in response to herbicide treatment compared to the non-treated control.

The number of published studies describing the efficacy and safety of sulfentrazone in specialty crops is limited, particularly with respect to cole crop production (Cutulle et al. 2018). Early season weed control is most important in conserving crop yields, particularly during the critical weed control period which is 21-35 DAP for transplanted cabbage and 15-30 DAP for transplanted broccoli (Latif et al. 2021; Weaver 1984). In our study, treatments that provided the best early season weed control (14-28 DAP), oxyfluorfen, sulfentrazone high, and *S*-metolachlor fb oxyfluorfen, also yielded the highest cabbage head weight in NJ (Table 2, Table 7). The use of

PRE herbicides, especially in poorly competitive crops such as cabbage and broccoli, has the potential to greatly reduce labor required to reduce weed competition during this critical period of control. Amisi (2005) estimated that the cost of hand labor, assuming a minimum wage of $6 per hour, for hand weeding up to the critical control period of cabbage to be $192 per hectare. Gianessi and Sankula calculated that labor associated with weed control in broccoli, without the use of herbicides, was 20 hours per hectare (2003).

The incorporation of sulfentrazone into weed control programs, especially when used in combination with other herbicides, has the potential to increase yields and reduce labor required to produce quality cabbage and broccoli in Northeastern and Mid-Atlantic production environments. In Florida, Sandhu et al. (2022) found that sulfentrazone was not effective alone in controlling weeds, but when applied PRE-T in combination with POST halosulfuron applications, nutsedge (*Cyperus* spp.) suppression was achieved in tomato. Similarly, they reported that sulfentrazone treatments could be as effective as industry standards for nutsedge control, but no adequate control method exists in strawberries or tomatoes in Florida. Other specialty crops, such as rhubarb and strawberries, have special local needs labels for sulfentrazone use in Oregon to control broadleaved weeds. Sulfentrazone may be able to supplement existing weed control programs depending on specific weed spectrum and timing of emergence of weeds. For example, sulfentrazone could serve as a potential replacement for oxyfluorfen applied PRE-T, with oxyfluorfen being able to be used with a POST-T application, instead. Crop tolerance for cole crops within these combination applications would need to be evaluated to guide use recommendations. Although utilizing two PPO inhibitors sequentially may not be the best-case scenario for managing herbicide resistance, it highlights the need for new herbicide development and registration in cole crops with different modes of action.

Another possibility to include sulfentrazone into weed control programs in the Northeast and Mid-Atlantic would be to focus on the key weeds controlled. Sulfentrazone is labled for use to suppress yellow and purple nutsedge (*Cyperus rotundus*), as well as annual sedges (*Cares* spp.) when applied PRE or POST as directed (1.06 kg ha^{-1}). Sulfentrazone also has activity against field bindweed, another key species that is left behind after oxyfluorfen applications. Treflan can currently be used to control field bindweed in cole crops, but due to injury concerns in cool, wet conditions along with the need for physical incorporation, many avoid utilizing it in weed control programs. More work needs to be done to further contextualize the conditions under which sulfentrazone would be preferable compared to current grower weed control standards in cole crops.

Differing planting restrictions after herbicide applications may highlight another potential use for sulfentrazone on diversified operations. Sulfentrazone has no planting restrictions for most vegetables, soybeans, and corn, while rye and wheat have a 4-month planting restriction. On the other hand, oxyfluorfen has a 10-month planting restriction for cereal grains and 0-30 days for some transplanted vegetables. Future research with sulfentrazone in cole crops in Northeastern and Mid-Atlantic conditions should focus on incorporating it into existing weed control programs to supplement and broaden the weed spectrum of control.

Practical Implications

Although cole crop production is significant in the Northeast United States, there are limited weed control options available to growers. Weeds are significant contributors to yield loss in eastern cabbage and broccoli production, due to direct interference for light, water, and nutrients and indirect interference such as contributing to pest and disease incidence in production environments. Sulfentrazone is an herbicide that can control broadleaved weeds such as redroot pigweed and common lambsquarters, but environmental conditions, such as soil pH and texture, can impact its efficacy and safety in crops. Published sulfentrazone studies evaluating crop safety and efficacy are limited in this region, which makes use recommendations difficult. In this study, researchers in NY and NJ evaluated the crop safety and efficacy of weed control of sulfentrazone applied PRE at two rates to acidic silt-loams. This active ingredient was compared in safety and efficacy to oxyfluorfen applied PRE, the grower standard, as well as an injurious, but effective, herbicide combination not recommended to growers, *S*-metolachlor (immediately post-transplant) fb oxyfluorfen (14 d later). Results of this study demonstrate that sulfentrazone high was effective in controlling weeds such as hairy galinsoga, smartweeds, and common ragweed in NY and NJ, particularly early in the season. Cabbage was more sensitive to stunting related to weed competition, whereas broccoli was more sensitive to herbicide injury. However, at 233 g ai ha $^{-1}$, sulfentrazone caused transient crop injury that did not impact yields relative to the grower standard, oxyfluorfen. Sulfentrazone when applied pre-transplant at 233 g ai ha $^{-1}$ has the potential to be an effective tool in a weed control program in Northeast and Mid-Atlantic conditions for broccoli and cabbage production.

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Table 1. Average monthly rainfall in 2021 and 2022 and 30-yr monthly rainfall average for Geneva, NY and Bridgeton, NJ.

	Geneva			Bridgeton		
Month	2021	2022	30-yr avg	2021	2022	30-yr avg
	------------------------------------ mm------------------------------------					
May	49	42	83	82	127	89
June	64	117	92	74	71	106
July	135	18	95	216	51	113
August	120	23	89	101	55	124
September	31	27	83	109	101	112
October	205	5	97	96	150	96
November	30	39	65	18	91	80
Total	*634*	*271*	*604*	*695*	*646*	*720*

Table 2. Visual evaluation of weed cover at 14, 21, 28, and 42 DAP as affected by residual herbicides at Geneva, NY, in 2021 and 2022, and at Bridgeton, NJ, in 2022.

Treatment[a]	Rate	14 DAP[b]	21 DAP[c]	28 DAP	42 DAP
Herbicide	g ai ha^{-1}	%			
Non-treated weedy control	-	6 a	26 a	52 a	72 a
Oxyfluorfen	560	0 c	0 c	0 c	2 c
Sulfentrazone	116	1 b	7 b	13 b	27 b
Sulfentrazone	233	0 bc	2 bc	4 bc	21 b
S-metolachlor fb oxyfluorfen	715 fb 210	0 bc	0 c	0 c	1 c
Fixed source of variation		*P* > *F*			
Herbicide		<0.0001	<0.0001	<0.0001	<0.0001
Crop		0.7551	0.0074	0.1428	0.0042
Herbicide x crop		0.2768	0.5580	0.8562	0.0479
Location		0.0701	-	0.0896	0.0805
Location x herbicide		0.1544	-	0.1008	0.0914
Location x crop		0.1110	-	0.1202	0.0505
Location x herbicide x crop		0.0602	-	0.7067	0.0569

[a] Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

[b] Abbreviation: DAP, d after planting.

[c] Data represents only NY; NJ did not collect weed cover data at this observation point.

Table 3. Hairy galinsoga at Bridgeton, NJ, and common ragweed and smartweed density at Geneva, NY, 14 and 28 DAP as affected by residual herbicides in 2021 and 2022.[a]

		GASCI[b]		AMBEL		POLXX	
Treatment[a]	Rate	14 DAP	28 DAP	14 DAP	28 DAP	14 DAP	28 DAP
Herbicide	g ai ha^{-1}	---------- m^{-2} ----------					
Non-treated weedy control	-	70 a	29 a	2 a	9 a	7 a	21 a
Oxyfluorfen	560	1 c	1 c	1 ab	1 bc	1 b	1 b
Sulfentrazone	116	23 ab	28 a	2 a	3 a	8 a	14 a
Sulfentrazone	233	7 bc	11 b	0 ab	2 ab	2 ab	2 b
S-metolachlor fb oxyfluorfen	715 fb 210	3 c	1 c	0 b	0 c	0 b	0 b
Fixed source of variation		---------- $P > F$ ----------					
Herbicide		<0.0001	<0.0001	0.0029	<0.0001	<0.0001	<0.0001
Crop		0.4137	0.7567	0.0803	0.1007	0.2582	0.0518
Herbicide x crop		0.2456	0.6937	0.7166	0.3117	0.9508	0.7866

[a] Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

[b] Abbreviation: DAP, d after planting, AMBEL, common ragweed; GASCI, hairy galinsoga; POLXX, ladysthumb and prostrate knotweed combined.

Table 4. Total dicot and monocot weed densities 14 DAP and 28 DAP and total weed biomass at harvest as affected by residual herbicides at Geneva, NY, and Bridgeton, NJ, in 2021 and 2022.

		Dicot		Monocot		Weed DW
Treatment[a]	Rate	14 DAP[b]	28 DAP	14 DAP	28 DAP	
Herbicide	g ai ha^{-1}	----------------------- m^{-2} -----------------------				g m^{-2}
Non-treated weedy control	-	74 a	65 a	27 a	57 a	575 a
Oxyfluorfen	560	2 c	6 bc	0 c	1 d	9 c
Sulfentrazone	116	20 b	37 a	3 b	14 b	232 ab
Sulfentrazone	233	6 bc	14 b	0 c	3 c	67 b
S-metolachlor fb oxyfluorfen	715 fb 210	3 c	3 c	0 c	0 d	4 c
Site						
Geneva, NY		4 b	6 b	2	3 b	33
Bridgeton, NJ		22 a	43 a	2	8 a	66
Fixed source of variation		---------------------------- *P* > *F* ----------------------------				
Herbicide		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Crop		0.4932	0.0710	0.2937	0.3554	0.7024
Herbicide x crop		0.5676	0.9071	0.7767	0.8820	0.9708
Location		0.0018	0.0104	0.6918	0.0092	0.1295
Location x herbicide		0.0784	0.4531	0.0604	0.0301	0.1678
Location x crop		0.7685	0.5452	0.2204	0.4523	0.2488
Location x herbicide x crop		0.4966	0.7012	0.3604	0.9096	0.1020

[a] Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

[b] Abbreviation: DAP, d after planting; DW, dry weight.

Table 5. Visual evaluation of crop injury at 14, 21, 28, and 42 DAP as affected by residual herbicides and crop species at Geneva, NY, in 2021 and 2022.

Treatment[a]	Rate	14 DAP[b]	21 DAP	28 DAP	42 DAP
Herbicide	g ai ha^{-1}	%			
Non treated weedy control	-	0 b	0 d	0 c	0
Oxyfluorfen	560	1 ab	2 cd	4 b	0
Sulfentrazone	116	2 ab	5 bc	4 b	0
Sulfentrazone	233	9 a	13 ab	15 a	2
S-metolachlor fb oxyfluorfen	715 fb 210	4 a	21 a	22 a	1
Crop					
Broccoli	-	4 a	8 a	6	0
Cabbage	-	1 b	4 b	7	1
Fixed source of variation		P > F			
Herbicide		0.0012	<0.0001	<0.0001	0.0519
Crop		<0.0001	0.0003	0.6840	0.7207
Herbicide x crop		0.0876	0.2508	0.2632	0.9824

[a] Data were pooled across crop species or herbicides when the herbicide x crop interaction was not significant. Main effect means within a column followed by the same letters are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

[b] Abbreviation: DAP, d after planting.

Table 6. Visual evaluation of crop injury 14, 21, 28, and 42 DAP as affected by residual herbicides and crop species at Bridgeton, NJ, in 2021 and 2022.

					42 DAP	
Treatment[a]	Rate	14 DAP[b]	21 DAP	28 DAP	Broccoli	Cabbage
Herbicide		----------------------------------	----------	%	----------	----------------------------------
Non treated weedy control	-	0	1 b	0	61 a Y	70 a X
Oxyfluorfen	560	3	2 b	1	1 b X	2 cd X
Sulfentrazone	116	2	1 b	1	10 b Y	26 b X
Sulfentrazone	233	3	5 b	0	10 b X	19 bc X
S-metolachlor fb oxyfluorfen	715 fb 210	2	22 a	2	0 b X	0 d X
Crop						
Broccoli	-	0 b	3 b	0 b	-	-
Cabbage	-	5 a	7 a	1 a	-	-
Fixed source of variation		-------------------------------	----------	*P* > *F*	----------	-------------------------------
Herbicide		0.0945	0.0002	0.2681	<0.0001	
Crop		<0.0001	0.0007	0.0193	0.0014	
Herbicide x crop		0.3320	0.7691	0.5558	0.0050	

[a] Data were pooled across crop species or herbicides when the herbicide x crop interaction was not significant. Main effect means followed by the same letter within a column (a-c) or row within crop species (X–Y) are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

[b] Abbreviation: DAP, d after planting.

Table 7. Crop yield at Geneva, NY, and Bridgeton, NJ, and crop head circumference at Bridgeton, NJ, as affected by residual herbicides and crop species in 2021 and 2022.

Treatment[a]	Rate	Yield			Head circumference	
		Geneva	Bridgeton			
			Broccoli	Cabbage	Broccoli	Cabbage
Herbicide	g ai ha^{-1}	------------------- g head^{-1} -------------------			---------- cm head^{-1} ----------	
Non treated weedy control	-	286	380 X	533 c X	41 b X	38 b X
Oxyfluorfen	560	404	569 Y	1,981 a X	51 a Y	61 a X
Sulfentrazone	116	345	463 Y	1,159 b X	47 a X	50 a X
Sulfentrazone	233	305	501 Y	1,424 ab X	49 a X	54 a X
S-metolachlor fb oxyfluorfen	715 fb 210	340	578 Y	1,761 ab X	51 a Y	59 a X
Crop						
Broccoli	-	148 b	-	-	-	-
Cabbage	-	553 a	-	-	-	-
Fixed source of variation						
Herbicide		0.2184	<0.0001		<0.0001	
Crop		<0.0001	<0.0001		0.0016	
Herbicide x crop		0.8804	0.0002		0.0162	

[a] Data were pooled across crop species or herbicides when the herbicide x crop interaction was not significant. Main effect means followed by the same letter within a column (a-c) or row within crop species (X–Y) are not significantly different from each other according to Tukey's honest significance test ($P \leq 0.05$).

Chapter 3: Labor and Weed Management

Weed management remains a top priority for vegetable growers worldwide. In labor-intensive crops, such as cabbage and broccoli, herbicide use has increased profitability by improving yields, reduced root damage potential that frequently resulted from cultivation, and reduced the amount of time spent hand weeding. However, the future utility of herbicides as the main form of weed control in vegetable production may be threatened by many factors, such as the development of herbicide resistance in common weed species and changes to the regulatory environment, opening the doors for novel technology for weed management. The introduction of novel weed control technology may influence agricultural community dynamics, particularly agricultural labor pool characteristics. This chapter will briefly consider how the intentional adoption and use of this technology may affect farms and farm workers.

The US labor pool has been changing over time. For example, the average age of agricultural workers has been steadily increasing; in 2019, the average age of farm laborers, graders, and sorters was 39 years, a 6-year increase from 2006 (USDA ERS 2023). As another example, the proportion of women laborers has increased in the past 10 years. As of 2019, women accounted for 26% of all hired farmworkers compared to 19% in 2006. This shift may be the result of the adoption of more mechanical aids in agriculture that lessens the physicality required to do agricultural work (USDA ERS 2023). The total number of people engaged in on farm work is also changing. Between 1950 and 2000, the number of hired farm workers fell from 2.3 million to 1.13 million. From 1950-2000, the number of family farmworkers (defined as self-employed farmers of unpaid family members) has decreased as well, with a greater decrease than in hired farmworkers, from 7.6 million to 2.06 million employed. The decrease in the numbers of farmworkers may also be reflective, of the impact that labor-saving technologies, including herbicides, have had, in addition to the consolidation of farms (USDA ERS 2023). However, with a decrease in the numbers of family farmworkers, it’s possible that the burden of labor costs has increased as well.

State and federal-level minimum-wage laws have a huge impact on the affordability of agricultural labor. In California, minimum wage laws have phased in a minimum wage increase to $15.00 per hour by 2022, which is a 7% increase from 2017, with the possibility of increased overtime wages after 40 hours per week worked. Previously, the overtime limit was after 60 hours per week worked. New York has also finalized an agricultural worker overtime regulation change (Khan 2023). This increase in wages ensures that essential hired agricultural workers are fairly compensated for the work they do, although this may result in a significant increase in cost burden for producers in the coming years.

Herbicides are a commonly used tool for controlling unwanted vegetation; their application in vegetable crops has been shown to reduce labor needs associated with weed management. However, the development of new herbicides, especially those that could be used in specialty crops, has stalled. From the 1980s to early 2000s, the majority of new registrations in specialty crops have been emergency use or special local needs labels. During this time period, several pesticides for specialty crops were deregistered or removed from the market. Since then, approximately 26 minor-crop herbicides and fumigants have suffered this fate across the United States and Canada (Fennimore and Doohan 2008). For example, methyl bromide, a fumigant used to reduce pathogens, weed seeds, and propagules, was subject to a phase-out program due to air quality concerns caused by volatile organic compounds. As recently as last year, clomazone is no longer labeled for use in cabbage. Recently, the discussion of PFAS (perfluoroalkyl and polyfluoroalkyl substances), better known as “forever chemicals”, has raised concerns with the use of certain chemicals in vegetable production environments. These chemicals are commonly used substances that are found in a variety of household goods, ranging from cookware to clothing. In the state of Maine, there is some debate on whether the active ingredient oxyfluorfen may meet the definition of PFAS (due to its chemical structure); this designation could have significant impacts on grower ability to utilize this chemistry in brassica systems (Leigh 2022). Maine is a significant broccoli producing state in the eastern US (Atallah et al. 2018) and there are grower concerns that available alternatives are not as effective. Any potential replacements, or new weed control options, would have to be cost effective, safe to use in crops, and work just as well as the chemistries currently used in crop production.

Another factor that threatens the efficacy and feasibility of using herbicides in vegetable production is herbicide resistance. Herbicide resistance is defined as “the inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type” by the WSSA (1998). The International Survey of Herbicide Resistant Weeds reports that there are 522 unique cases of herbicide resistance as of July 2023. Although the majority of reports come from agronomic crops, fruits, nuts, and vegetable systems are not immune to resistance development (Boyd et al. 2022). However, the lack of numerous evolution and dispersal events are likely due to a variety of factors, which includes the continued use of hand weeding (Boyd et al. 2022). Hand pulling weeds that escaped control is a labor-intensive practice that can reduce seedbank contributions and can help prevent development and spread of herbicide resistant weeds. Alternatively, less hand weeding due to high cost and lower availability of labor could contribute to herbicide resistance becoming a more serious concern in vegetable crops. With more resources aimed at detecting incidences of resistance in vegetable systems, weed scientists may find that herbicide resistance is a more serious problem than previously thought in vegetables. The onset of herbicide resistance in vegetable production reduces the efficacy of herbicides as a tool for weed management and may increase the labor required to maintain weeds adequately controlled on an operation.

If labor and herbicides are limited in the future, growers may need to look towards novel weed control technologies to eliminate weeds. The term “novel weed control technology” can be applied to a variety of different tools for weed management. To date, there is a significant amount of variability in how they are propelled, how they discriminate among crops and weeds, and how they removed unwanted vegetation. For example, some of these novel weed control technologies can be tractor mounted while others are self-powered. These technologies can incorporate a variety of different actuators to kill weeds, some of which are commonly used in traditional farm implements such as cultivators or herbicide sprayers, which others are applying thermal energy via lasers (Machine Design 2018). Some incorporate machine-learning algorithms to detect weeds while others are non-selective with respect to removal. Some companies are actively engaged in direct sales whereas others engage in a contract-based service model of operation. The companies developing these innovative solutions for weed control come from places like the Western US or Europe, where weed control is a necessity but the current management options, whether it be labor shortages or regulatory constraints with respect to chemical control, are not adequate for their current weed management needs. The size and value of the operations may also play a role. Currently, much of the research and evaluation has focused on large acreage and extremely high value farming systems in California and Arizona, although some introgression is occurring into other regions. In the US, this creates a disparity in the technologies that are available to growers across the country. Smaller growers are constrained in the types of technologies available, applicable, and accessible to them and their operations.

Throughout history, adoption of new technology has advanced agriculture by reducing time, effort, and labor required. Tractors, mechanical corn pickers, the cotton gin, herbicides, amongst other inventions, have been adopted by many farmers and subsequently revolutionized agriculture. Recently, farm owners and operators have begun to invest in novel labor-saving technologies in agriculture. For the produce industry, mechanization has served as a useful tool for some commodities, particularly during harvest (Calvin et al. 2022). Not every commodity is as easily mechanized as others, oftentimes making these tools specific to a specific product. Another example of labor-saving adoption of novel technology occurs in the dairy industry. Automated milking parlors become economically comparable with traditional milking systems when labor costs increase beyond the current minimum wage to something between \$25 and \$32 an hour (Dairy-Cattle 2019). In weed management, these economic estimates have not been calculated as extensively. These types of labor cost projections may be useful for a vegetable grower to know in order to calculate when the investment in a new technology may be worth it.

There are other barriers for adopting new practices and technologies for weed management. The Northeast and Mid-Atlantic US are regions characterized by much smaller fields and more diversified operations than the west and parts of the Southeast. Since the majority of the agricultural technology companies that have these novel technologies on the market have based their product development on the scale and environmental conditions for vegetable growers in the West, there are less technologies that are applicable for Northeast and Mid-Atlantic growers. Another constraint in Eastern fruit and vegetable production is that the operations are more diversified, making it necessary to utilize equipment that has the flexibility to adapt to a variety of commodities. Grower demographics may also influence the utilization of new technology; the average age of farmers in the US is 57.5, which may also act as a barrier for adoption due to age-related risk preferences as well (USDA NASS 2017). Risk-related considerations do impact adoption processes of agricultural technology; until the technology or practice has proved itself, growers may be unwilling to risk investing it (Marra et al. 2003). To facilitate increased adoption in these types of technologies, there should be an intentional push for field days where growers are able to ask questions, witness the technology in action, and chat with others who have adopted the technology. However, this type of technology normally represents large, fixed costs, which makes it more likely for the largest growers to adopt novel weed control technology first.

On the other hand, a factor that may accelerate adoption of these technologies is labor shortages faced due to US closed-border policies or stricter enforcement of existing immigration policies (Carolan 2020). These labor shortages also contribute to additional adoption of technology in other agricultural sectors that rely on consistent farm labor such as fruit and vegetable production. A USDA ERS report that modeled the impacts of reduced unauthorized workers in agriculture indicated that the fruit and vegetable sector would be the hardest hit (Zahniser et al. 2012). Another report from the USDA ERS reported that the three main strategies employed to counteract high farm labor costs in fruit and vegetable production were to adopt mechanization, depend more on H2-A guestworker programs, or to reduce domestic production of labor-intensive crops that are no longer competitive with imports from lower-wage countries (Calvin et al. 2022). Predicting the likely outcome of adopting different strategies informs the decision-making of farmers when it comes to weed management (Moss 2008). Growers and companies with access to some of these novel technologies have begun automation out of an abundance of caution since future immigration policies and access to stable agricultural workforce are uncertain.

The share of hired crop farmworkers who are not legally authorized to work in the US has increased from 14% in 1989-91 to around 48% in recent years (ERS 2022). The Northeastern US is a region heavily impacted by expedited removal immigration policies due to its proximity to external boundaries (100 air-miles), which in turn has consequences for the stability of the workforce that is not legally authorized to work (ACLU 2023). The only federal guestworker program, H2-A, allows for growers to employ foreign laborers in seasonal jobs if no US workers are available (Calvin and Martin 2022). Physicality of agricultural work, seasonality of employment, and higher wages in urban centers dissuades many domestic workers from accepting these jobs. New York is one of the leading states with US H2-A positions for temporary agricultural employment available, with 8,482 available in 2020 (USDA ERS 2023). An indicator of the farm labor shortage is the increased number of H2-A positions requested from 48,000 in 2005 to 371,000 in 2022 (USDA ERS 2023). H2-A visa guestworker programs generally have higher costs associated with them but have also increased the stability of the workforce as well.

The historical context for the influx and growth of foreign-born agricultural workers in the US shed light on the current landscape of domestic agriculture. US agriculture has historically depended on foreign-born and marginalized sources of labor, since even before its founding as a country. West African people were enslaved and brought over to support large-scale agriculture to the American colonies starting in the 1600s. After the Civil War, sharecropping was a practice used that further marginalized descendants of enslaved people and poor white farmers in the Deep South up until the 1940s. Landowners allowed tenants, or sharecroppers, to farm on small plots of land in exchange for a portion of the crop (Duke Sanford World Food Policy Center n.d.). This practice set up a power imbalance between tenants and owners of the land. On the other side of the country, The Gold Rush prompted an influx of primarily Chinese immigrants and in the following decades, they became a significant portion of the agricultural labor in the Western US. The Chinese Exclusion Act of 1882 caused many of these immigrants to be replaced with others from Japan, the Philippines, Korea, and other Southeast Asian countries (Good Food Finder 2022). Production of sugar, rice, pineapple, taro, coffee, cherry, strawberries, as well as other specialty crops, all have historic ties to Asian immigrant labor. Discriminatory laws in multiple states forcibly removed land-owning privileges from non-American farmers in the early 20th century. As a result of WWII worker shortages, a series of agreements between Mexico and the United States led to the Bracero Program from 1942 to 1964, which allowed Mexican men to work legally in the US for short periods of time (Calvin and Martin 2023). Many California growers were concerned about the labor shortages that would come about at the end of the Bracero Program, particularly in regards to the processing tomato and lettuce industries. The Bracero Program was the first guestworker program, after which the H-2A program was introduced to provide visas for nonimmigrant guestworkers.

Government policies continue to greatly impact agricultural communities, sources of labor, and labor availability. Farmworkers are a group that have historically been mistreated and continue to suffer exploitations, whether they are authorized or unauthorized to work in the US. Through collective bargaining and leveraging their unique skills, farmworkers across the country have been able to advocate for better wages and working conditions. In 1975, the California Supreme Court banned the use of the short-handled hoe, used to weed and thin lettuce, due to lower back injuries sustained by farmworkers (Murray 1982). Currently, farmworkers and labor rights advocates are calling for a federal heat protection standard to address the rate of heat stress injuries in agricultural work. This topic is only going to become more important as climate change increases the frequency of adverse or extreme weather events, such as dangerously hot working conditions. Worker-led programs and coalitions designed to protect farmworker rights, such as the Fair Food Program, have been successful in developing a code of conduct backed by some of the world’s largest retail food brands (Council of Immokalee Workers 2022). A bill offering a path to citizenship for undocumented farmworkers that has received bipartisan support and has been passed by the House of Representatives a few times, but has not advanced past the Senate. Farmworkers across the country both support and oppose this bill. Many who oppose the proposed legislation believed that there were unfair provisions that created greater instability for immigrants in the United States, including changes to the H2-A program and the requirement to use an automated system to check the legal status of their workers (6 years after the law was implemented). Supporters of this bill stated that although not fully comprehensive, this was a great step in the right direction to offer protections and benefits that many farmworker advocacy organizations have been pushing for (Held 2023). A combination of government policies, farmworker-led advocacy, and technologies that reduce physical strain have the potential to improve working conditions for agricultural workers

Between 2002 and 2014, there was a decline in the number of field and crop workers by 146,000 while their wages rose by 12% (New American Economy 2023). Both foreign-born farmworkers and Americans working in agriculture are getting older. However, the USDA ERS Rural America at a Glance report, cited an observed decline of employment in agriculture coupled with an increased output and productivity around the early 2000s. Since then, the employment rate in agriculture has been stagnant (USDA ERS 2022). Technological advances in agriculture can make the existing labor more efficient, even when the workforce is aging and shrinking. For example, when the Bracero program expired in 1964, there were labor shortage issues that were addressed by the adoption of a mechanical harvester for processing tomatoes (Astill et al. 2020). Agricultural workers are being more adequately compensated for the essential and skilled labor that they provide that is not able to be automated. However, automation or mechanization can free up farm owner-operator time as well, that can be dedicated towards family or leisure. Historically, the adoption of this technology has allowed non-hired farm labor, or family members, to work off-farm. This contributed to farm viability by allowing a diversity of income flows for the family.

There are many players involved in technological advances to agriculture and the field of weed science as a whole. Researchers, government entities, and agricultural technology companies are all key players in the research and development of these weed management, labor-saving technologies. Institutions such as high schools, trade schools, and colleges, should be included in the conversation as new career options begin to arise as technology continues to integrate into agriculture. These institutions have the unique position to be able to promote and incentivize working in agriculture by providing job security via transferable skills to young people considering their career options. It’s important to continue to work across disciplines such as sociology and economics to further understand factors that are essential in the decision-making process of produce growers and technological impacts on agricultural communities. These players may be able to bring up other considerations that may impact how novel weed control technologies are adopted and how they interact with their sociocultural context. Last but certainly not least, key players that should be involved in these conversations are growers and agricultural workers specifically. In order to fully understand what needs, barriers, and concerns these important stakeholders have with the adoption of novel technology, they need to be included in the conversations. An approach that has gained traction in European research spheres is the concept of Responsible Research and Innovation (RRI), which takes into consideration that these processes of introduction, adoption, and successful transition within communities are dynamic and multi-directional. Individuals will be engaging with technology with a specificity that’s unique to the needs and realities of their communities. RRI involves a variety of stakeholders and incorporates topics such as sustainability, ethics, human health, and impacts on communities into the decision-making process of developing a novel technology or introducing a new practice.

Even though there will be shifts in the labor landscape and impacts may be felt on the community as labor-saving technology is adopted, it’s important to look at it from a holistic perspective. There are positives to reducing the labor or changing the types of labor required in specialty crop production. At this point in history, agriculture as an industry has the opportunity to adopt new technology to reduce its dependence on exploitative labor practices. A reduction in exposure to occupational hazards such as pesticides or wildfire smoke, while less time may be spent engaging in physical labor are just two additional positives. Climate change will contribute to more extreme weather patterns across the US, coupled with the potential for increased pest and disease pressure. With some intentionality, the impacts of the adoption of novel technologies can be mitigated.

Although this adoption of novel technologies will not happen overnight, commercially available robotic weeders, steamers, machine-guided cultivators are already in use in many Western production environments. As the necessary changes in the machines occur to further accommodate differences in commodities, sizing, and terrain between Western and Northeastern production environments, agricultural communities and researchers should prepare for these possible shifts in labor needs that may come as a result of adoption. Utilizing the lens of RRI, the adoption of novel weed control technologies in the Northeast with intentionality and care for the communities that will most benefit and be most impacted by it.

Since the early 2000s, specialty crop weed scientists have hypothesized that the future of weed control is a more integrated and holistic approach, to reduce dependence on any one control method. As the discipline moves towards that more integrated approach, addition of new technologies would help fill gaps and needs that shrinking labor pool and limited control chemicals leave behind. Adoption of novel agricultural technologies will likely shape the composition of farm labor throughout the coming years as well. For example, if novel weed control technology is adopted throughout the Northeastern US, the proportion of farmworkers vs equipment operators as a percent of agricultural employment may shift in response, similar to the age and sex differences observed in the composition of agricultural laborers as a result of increased mechanization. As these technologies are adapted and introduced to Northeast production environments, responsible and intentional adoption of the technology and transition of potential displaced workforce should be considered by researchers, educational institutions, and policy-makers. Trade schools, colleges, and high schools need to be thinking about training the up-and-coming workforce to accommodate future needs such as building, operating, and repairing robotic equipment, programming, and data analysis. As agricultural innovation begins to approach weed management, a shift in employment opportunities will begin to occur. These technologies are unlikely to completely replace labor in weed management, but instead may provide a way to more efficiently use the changing labor pool, while providing an improved work experience for those employed in agriculture.

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