Title

Developing management strategies for branched broomrape in California processing tomatoes

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Developing Management Strategies for Branched Broomrape in California Processing Tomatoes

By

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Abstract

This research aimed to evaluate, develop, and refine chemical and cultural controls for branched broomrape in processing tomato, a quarantine pest in California. Branched broomrape is an obligate parasite that can attach to the roots of a wide range of plants, particularly tomato and other agricultural crops. Interest in strategies for management of branched broomrape in processing tomatoes has been growing in California and Chile where tomatoes are major cash crops.

Chapter 1 aimed to evaluate and develop herbicide programs based on programs developed in Israel for Egyptian broomrape control in tomato. Crop safety and efficacy studies evaluating preplant incorporated (PPI) sulfosulfuron paired with chemigated imazamox as well as limited treatments including chemigated rimsulfuron were conducted in California and Chile. Chemigated imazamox alone and paired with PPI sulfosulfuron generally reduced broomrape emergence; however, chemigated imazamox resulted in unacceptable crop injury in most trials at rates higher than 9.6 g ai/ha. Chemigated rimsulfuron alone or paired with PPI sulfosulfuron reduced broomrape emergence and did not injure tomatoes. Over several field trials, chemigated imazamox did not have adequate safety in tomato and will not be pursued further

In the 2021 and 2022 studies evaluating the crop safety and efficacy of chemigated imazamox, there were differences in crop injury between field sites in California: imazamox-treated tomatoes in the Davis site only experienced minor early season injury while tomatoes at the Woodland site were severely injured or killed. Chapter 2 aimed to investigate the cause of this discrepancy in injury. A study was conducted to investigate imazamox sorption in four California soils to determine if differences in herbicide adsorption played a role in variable crop injury observed in the California field trials. To determine the sorption capacity of imazamox of each soil, a batch equilibrium study was conducted. There were significant differences in sorbed imazamox: the clay soil had the highest adsorption, followed by the sandy loam soil, while the loam soils from the Davis and Woodland trial sites had the lowest adsorption and were not significantly different from one

another. The results from this study illustrate only minor differences in imazamox adsorption among the soils tested which suggests that soil type was likely not a major factor contributing to the discrepancy in imazamox injury in the earlier field trials.

Chapter 3 aimed to further develop and refine chemigated rimsulfuron treatments. Following the lack of crop safety of chemigated imazamox and positive results of chemigated rimsulfuron in field studies in 2022, field research was conducted in 2023 and 2024 to evaluate various application timings of chemigated rimsulfuron alone, PPI sulfosulfuron paired with chemigated rimsulfuron, as well as foliar maleic hydrazide alone and in combination with PPI sulfosulfuron and chemigated rimsulfuron. In 2023, all treatments with a total of 70 g ai/ha rimsulfuron alone or paired with PPI sulfosulfuron reduced broomrape emergence 77-92% compared to the nontreated control ($P<0.0001$). In 2024, all rimsulfuron treatments reduced broomrape emergence 68-86% compared to the nontreated control ($P<0.0001$). In both years, five applications of foliar maleic hydrazide reduced broomrape emergence through at least midseason; however, in 2024 a late flush of broomrape was observed in late summer in these treatments. The 2024 combination treatment of PPI sulfosulfuron, chemigated rimsulfuron, and foliar maleic hydrazide was the best treatment overall, reducing broomrape emergence 96% versus the nontreated control ($P<0.0001$). Under a recently approved 24c label, growers can currently use three applications of rimsulfuron applied via chemigation to suppress broomrape in known infested fields or to reduce the risk of broomrape in fields of concern for this quarantine pest. Promising results from sulfosulfuron and maleic hydrazide suggest that the registration of additional herbicides could help develop even more robust branched broomrape management programs.

Chapter 4 aimed to evaluate integrated cultural control practices for branched broomrape management. Although there are now approved herbicides for in-season management, the development of integrated pest management strategies is needed to reduce the current infestation and mitigate the spread of this highly-regulated parasitic weed. Herbicide efficacy research was

conducted in 2020 and 2021 in a field known to be highly infested with branched broomrape; however, during the 2021 experiment no broomrape emerged in any plots. Because tomato cultivar and planting dates differed between the two years, several experiments were conducted to evaluate the impact of cultivar and transplant date on broomrape parasitism in processing tomato. A greenhouse study to evaluate variation in broomrape resistance across 20 cultivars, including the cultivar planted in the 2021 trial ('SVTM 9024') and 19 other top commercial cultivars was conducted in 2022 and repeated in 2023 and 2024. Resistance was evaluated based on ability to host broomrape as well as temporal differences in broomrape emergence. In field studies, variation in resistance was also evaluated, with several commercial processing tomato varieties and grafted combinations evaluated during 2022, 2023, and 2024. Planting date studies were also conducted in 2022 and 2024 to evaluate the effects of delayed tomato transplanting on broomrape emergence. Results from the 2022 greenhouse screening indicated that all cultivars, including 'SVTM 9024', were susceptible to broomrape parasitism, but that there could be variation in temporal emergence. The 2023 greenhouse studies confirmed this, with significant variation in the timing of broomrape emergence between 'SVTM 9025' and 'H9553' (P=0.05). The 2024 greenhouse study conducted in mid-summer had no broomrape emergence in any of the cultivars, likely due to hot conditions in the greenhouse leading to secondary dormancy of the preconditioned seed. Field cultivar studies conducted in 2023 and 2024 showed no significant differences in broomrape emergence among conventional or grafted cultivar combinations (P = 0.23, 0.74); results for the non-grafted cultivars were consistent with greenhouse studies. Broomrape was significantly reduced by later planting dates in the 2024 trial (P = <0.001), with no emergence at the latest planting date (June 10, 2024); 2022 planting date study was consistent with these results, with a 52% reduction on emergence at the later date, although differences were not significant (P = 0.21). Taken together, these experiments suggest that there is some variation in resistance among the tested commercial cultivars and delayed transplanting seems to reduce broomrape emergence and future research will seek to confirm this.

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CHAPTER 1

Evaluating the safety and efficacy of chemigation alternatives for branched broomrape control in processing tomatoes

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Abstract

Branched broomrape is an obligate parasite that can attach to the roots of a wide range of plants, particularly tomato and other agricultural crops. Interest in strategies for management of branched broomrape in processing tomatoes has been growing in California and Chile where tomatoes are major cash crops. In Chile, branched broomrape has been spreading throughout tomato growing regions for decades, while in California, it is not yet widespread but is a highly regulated quarantine pest. Multiple trials were conducted in California and Chile during 2021 and 2022 to evaluate herbicide programs for crop safety and efficacy on branched broomrape. Sequential treatment approaches were based on an Israeli-developed program of preplant incorporated (PPI) sulfosulfuron followed by several in-season chemigation treatments with imazapic. Additional treatments utilized imazamox or rimsulfuron as the chemigation herbicide alone or paired with PPI sulfosulfuron and a chemigated application of acibenzolar-S-methyl. In crop safety experiments, visual phytoxicity and yield data were recorded; in efficacy trials, broomrape emergence was recorded. The benchmark Israeli program reduced broomrape emergence and did not injure tomatoes but registration of imazapic for this use is unlikely in either California or Chile. In general, chemigated imazamox alone or paired with PPI sulfosulfuron reduced broomrape emergence; however, chemigated imazamox caused unacceptable crop injury in most trials at rates higher than 9.6 g ai/ha. Three applications of chemigated rimsulfuron alone or paired with PPI sulfosulfuron reduced broomrape emergence and did not injure tomatoes. Over several field trials, chemigated imazamox did not have adequate safety in tomato and will not be pursued further. A 24c Special Local Needs label was approved in 2023 that allowed chemigated rimsulfuron in California tomatoes. Future research will focus on refining the rimsulfuron protocol under a wider range of production practices in California and to support approval of this use in Chile.

Nomenclature

Sulfosulfuron, imazamox, imazapic, rimsulfuron, branched broomrape, *Phelipanche ramosa* L., tomato, *Solanum lycospersicum* L.

Keywords

Herbigation, chemigation, halosulfuron, acibenzolar-S-methyl, ALS inhibitors,

Introduction

Processing tomatoes are a major cash crop in the inland valley growing regions of California and Chile. In California, processing tomatoes are grown in the Sacramento and San Joaquin Valleys and rank as the number 10 crop in the state, worth over one billion USD per year (USDA NASS, 2021). In 2022, California growers produced 9.5 million metric tons of tomatoes on 90,000 hectares, with an average yield of 105 mT/ha (USDA NASS 2021). In Chile, processing tomatoes are grown in the O'Higgins and Maule regions of the Chilean Central Valley (Oficina de Estudios y Políticas Agrarias, Odepa, 2021). In 2020, Chilean growers produced just under 400,000 metric tons of tomatoes on 7,773 hectares with an average yield of around 50 mT/ha (Odepa, 2021).

Broomrapes (*Phelipanche spp.* and *Orobanche spp.)* are parasitic weeds native to the Mediterranean basin (Musselman 1994; Joel 2009). Broomrapes are obligate parasites that only germinates after receiving a chemical signal from a suitable host plant; seedlings then quickly attach to the roots of the host via a haustorium (Parker 2008). The above ground portion of the broomrape lifecycle is relatively short and consists of multiple flowering stems that lack chlorophyll and can quickly flower and produce thousands to hundreds of thousands of seeds that are highly persistent in the soil seedbank (Parker 2008). Some broomrape species have specialized and narrow host ranges, while others, such as *Phelipanche ramosa* and *Phelipanche aegyptiaca*, have wide host ranges that include many agricultural crop families grown in California and throughout the world (Musselman 1994).

In California, branched broomrape *(Phelipanche ramosa)* was first reported at the turn of the 20th century, but was thought to be eradicated through several decades of coordinated efforts by the processing tomato industry and state agencies (Gaimari and O'Donnell 2008; Jain and Foy 1989). However, in recent years it has been reported in several commercial processing tomato fields in Yolo County and now presents a major threat to both regional and statewide production due to its regulatory status (Kelch 2017; Osipitan et al. 2021). Branched broomrape is an "A-listed" quarantine pest in California requiring crop destruction if found and reported in a commercial field. In addition to the loss of the crop in the reporting year, a hold order is placed which bars the planting of host crops for several more years, presenting affected growers with a massive cumulative economic loss (Miyao 2017). In Chile, branched broomrape has been present since 1978 and is thought to be spreading throughout tomato growing regions but is not a regulated quarantine pest (Kogan, 1992; Galaz et al, 2022). In Chile, where tomatoes are typically grown under annual contracts, fields heavily infested with branched broomrape often are simply no longer contracted for tomato production due to the incurred yield losses (Galez, personal communication). Another broomrape species, Egyptian broomrape (*Phelipanche aegyptiaca*), has also been reported in three fields in the Sacramento Valley and is a "Q-listed" pest, the only known instance of the pest in the United States and requiring the same regulatory steps as an "A-listed" species (Miyao 2017). Historically, yield losses from broomrape globally range from 30% to as high as 80% in some systems (Parker 2008).

Many species of broomrapes are widespread throughout the Mediterranean basin, and researchers in Israel developed a decision support system and treatment protocols for management of Egyptian and branched broomrapes that are present in their processing tomato systems (Eizenberg and Goldwasser 2018; Hershenhorn et al. 2009; Eizenberg et al. 2004; Hershenhorn et al. 1998). The "PICKIT" decision support system relies on a thermal time model (growing degree days) to predict broomrape phenological stages and, based on these predictions, ALS inhibitor herbicides are applied at very low rates at times intended to target specific broomrape life stages and attachment to the host crop (Ephrath et al. 2012; Eizenberg, et al. 2012). The Israeli protocol is based on preplant or water incorporated sulfosulfuron followed by multiple applications of imazapic as the in-season chemigation component; however, due to significant regulatory barriers to registering imazapic in California, our chemigation research pivoted to imazamox, which already has a registration in California (Goldwasser et al. 2021; Fatino and Hanson 2022). Field studies evaluating the crop safety and efficacy of imazamox began in 2021 and continued in 2022 in California and Chile. In 2022, rimsulfuron was also evaluated as a foliar and chemigation treatment following positive results as a chemigation material in Italian processing tomato systems (Conversa, et al. 2017). In 2022, acibenzolar-S-methyl, a plant defense activator, was evaluated in California as a chemigated treatment following positive results reported on broomrape species in sunflower and rapeseed (Fan et al. 2007; Véronési, et al. 2009).

Materials and Methods

California Crop Safety 2021/2022

Four experiments were conducted in 2021 and 2022 to evaluate the crop safety of several herbicides used for branched broomrape control in processing tomatoes under California growing conditions at the UC Davis Plant Sciences Field Facility near Davis, CA (38°45'29.1"N 121°46'15.0"W; Table 1). The site did not contain broomrape; these experiments focused on crop safety of sulfosulfuron and imazamox in 2021 as well as rimsulfuron in 2022 (Tables 2, 3). The soil composition at this site was 44% sand, 36% silt, and 20% clay with an organic matter content of 1.85% and a pH of 7.40. Plots were 12 m long on 1.5 m beds with one plant line in the center of each bed. ‘HM 58841’ processing tomato transplants were planted at 30 cm spacing. Each bed had two 22 mm drip lines buried 30 cm deep in the center of the bed with 0.6 L/hr emitters spaced every 30 cm; one line ran the full length of the beds and was used for crop irrigation and the second line was terminated at the beginning and end of each plot and was used to apply the chemigation treatments. Plots were arranged in a randomized complete block design with four replications. Preplant incorporated (PPI) herbicides were applied using a backpack sprayer and three-nozzle boom delivering 187 L/ha with TeeJet AIXR 11002 nozzles. PPI treatments were mechanically incorporated with a power incorporator and bed shaper after application. Tomatoes were mechanically transplanted with a three-row transplanter. A redundant water delivery system was constructed to deliver irrigation water to the secondary chemigation drip lines and chemigated herbicide injections were made using CO_2 to push a chemigation mix into individual plots (Fig. 1). Chemigation applications were made to simulate a commercial application in which a grower would apply a chemical during an irrigation set through the irrigation system, in this case, subsurface drip irrigation (Tables 2, 3). Chemigation applications were made according to a growing degree day schedule similar to that of the PICKIT system (Eizenberg and Goldwasser 2018). Herbicide solutions were mixed in 3 L bottles and injected into individual plots over 5-10 minutes, followed by one hour of irrigation to flush lines. Visual plant phytotoxicity (% vigor reduction, stunting, chlorosis) data were collected throughout the season. Fruit was harvested from a 1-meter square section of row at commercial fruit maturity. Data were analyzed with a one-way analysis of variance followed by Tukey's HSD test in RStudio version 1.2.5033 using the agricolae package (Kniss and Streibig, 2018).

Chile Efficacy 2021

This experiment was conducted in a commercial field near Santa Cruz (34°39'57.2"S 71°22'22.7"W), 180 km south of Santiago, Chile. The experiment was arranged in a randomized complete block design with four replicates. Each plot consisted of a 1.5 m bed that was 17 m long. PPI sulfosulfuron was applied and mechanically incorporated prior to transplanting. 'HMX7883' tomato plants were hand transplanted on January 19, 2021. This planting date, which was approximately 6 weeks later than typical for the region, was due to logistical challenges related to project funding. Foliar and PPI herbicide applications were made using a 'Solo 434' 18 L high-pressure motorized backpack sprayer with a 1.5 m wide boom equipped with 3 'Spraying Systems'

Tee-Jet 110015 nozzles spaced 50 cm apart, delivering 200 L/ha. Each bed had a single 16.2 mm dripline on the soil surface with 1.1 L/hr emitters spaced every 20 cm. Chemigation treatments were applied using Venturi-type injectors which use a pressure difference between the water line and the 20 L stock tank to draw a concentrated solution into a connected valve that mixes it with water in the hose (Figure 2, Table 4). Broomrape emergence was monitored in each plot with weekly field scouting and marking of emerged shoots. Visual plant phytotoxicity data were collected throughout the season and crop yield was measured in each plot. Data were analyzed with a one-way analysis of variance followed by Tukey's HSD test in RStudio version 1.2.5033 using the agricolae package (Kniss and Streibig, 2018).

Chile Efficacy 2022

This experiment was planted within a 53-hectare commercial tomato field near Pumanque (34°39'43.5"S 71°45'42.5"W), 230 km from Santiago, Chile. The soil at this site was 51% sand, 26% silt, and 23% clay with an organic matter content of 2.7% and a pH 6.0. The experiment was arranged in a randomized complete block design with four replicates. Each plot consisted of a 1.5 m wide bed that was 20 m long. One week before planting, the experimental site was inoculated by hand with 3g *Phelipanche ramosa* seed per bed. Each bed had a single 16.2 mm diameter dripline buried 5 cm deep in the center of the bed with 1.1 L/hr emitters spaced every 20 cm. PPI sulfosulfuron treatments were applied using a 'Solo 434' 18 L high-pressure backpack motorized sprayer with a 1.5 m wide boom equipped with 3 'Spraying Systems' Tee-Jet 110015 nozzles spaced 50 cm apart, delivering 300 L/ha and mechanically incorporated prior to transplanting. The experiment was hand transplanted on December 2, 2021, with 'H1657' transplants in a single plant line with 25 cm spacing. Chemigation treatments were applied with the previously described Venturi injector system (Fig. 2, Table 5). Broomrape emergence was monitored in each plot with weekly field scouting and marking of emerged shoots. Visual plant phytotoxicity data were collected throughout the season and crop yield was measured in each plot. Data were analyzed with a one-way analysis of variance followed by Tukey's HSD test in RStudio version 1.2.5033 using the agricolae package (Kniss and Streibig, 2018).

California Efficacy 2022

Efficacy trials field testing and validating PICKIT protocols and other herbicide treatments on branched broomrape in California began in 2020 in a commercial tomato field near Woodland, CA, (38°45'29.1"N 121°46'15.0"W) that was first reported to be infested with branched broomrape in 2019 (Fatino and Hanson 2022). In 2022, an efficacy study was conducted at this field site to evaluate sulfosulfuron, imazamox, and rimsulfuron (Table 6). The soil composition at this site was 48% sand, 33% silt, and 19% clay with an organic matter content of 2.13% and a pH of 7.20. Plots were 30 m long on 1.5 m beds. 'HM 58841' processing tomato transplants were planted at a 30 cm spacing in a single-line. Each bed had one 22 mm drip line buried between 20-25 cm deep in the center of the bed with 0.6 L/hr emitters spaced every 30 cm. The trial was arranged in a randomized complete block design with four replications. Tomatoes were mechanically transplanted with a three-row transplanter on May 3, 2022, with a later planted treatment on May 20, 2022 with a single-row transplanter. Herbicide applications were applied following the same protocols as the crop safety experiments, with PPI applications applied preplant and chemigated applications applied according to a growing degree day schedule (Table 6). Broomrape emergence was monitored in each plot with weekly field scouting and marking of emerged shoots. Data were analyzed with a one-way analysis of variance followed by Tukey's HSD test in RStudio version 1.2.5033 using the agricolae package (Kniss and Streibig, 2018).

Results and Discussion

California Crop Safety 2021

There were early signs of visual injury in plots treated with the higher imazamox rates in both crop safety studies (Treatments 5, 9, 10; Table 7). Noted symptoms included stunting, elongated stems, pale green and grey plants, and general vigor reduction. Midway through the season, the plants appeared to grow out of the most severe injury symptoms (Table 7). There were no significant differences in marketable tomato yield among treatments in either experiment, although there was a trend in lower yield in plots treated with the 28.8 and 38.4 g ai/ha rates of imazamox in the second experiment (Table 7). Based on the crop injury results from the 2021 trials, 28.8 and 38.4 g ai/ha rates of imazamox were not included in subsequent studies.

California Crop Safety 2022

There were no signs of visual injury from any herbicide treatment in either experiment (data not shown). In the first experiment, tomato yield ranged from 15.5 to 22.7 kg/m^2 and there were no yield differences among treatments (Table 8). In the second experiment, tomato yield ranged from 13.8 to 20.8 kg/m^2 and there were no yield differences among treatments (Table 8).

Chile Efficacy 2021

The first Chilean trial evaluated chemigated imazamox up to 38.4 g ai/ha for branched broomrape management. Chemigated imazamox alone at 19.2 g ai/ha, and chemigated imazamox at 19.2, 28.8, and 38.4 g ai/ha paired with preplant incorporated sulfosulfuron and chemigated imazapic paired with preplant incorporated sulfosulfuron significantly reduced broomrape emergence versus the nontreated control (Table 9). Chemigated imazamox at all rates, alone and paired with sulfosulfuron, injured tomatoes and significantly reduced tomato yield versus control and compared to the Israeli standard treatment of PPI sulfosulfuron followed by chemigated imazapic (Table 9). Tomato yield was variable due to the delayed transplanting date; however, compared to control, tomato yield reduction was severe in plots treated with the higher rates of imazamox (Table 9). The Israeli standard, preplant incorporated sulfosulfuron paired with chemigated imazapic, had the best performance overall, significantly reducing broomrape emergence and maintaining commercially acceptable yields.

Chile Efficacy 2022

The second Chilean research trial evaluated several combinations of herbicides for branched broomrape management. Individual broomrape shoots were counted (as opposed to the number of broomrape clusters counted in the California trials). There were limited differences among treatments; treatment 6 (rimsulfuron foliar) had more broomrape stems than treatments 2 (preplant incorporated sulfosulfuron, chemigated imazapic) and treatments 8 (preplant incorporated sulfosulfuron, chemigated imazamox) (Table 10). Chemigated treatments tended to have lower broomrape emergence than foliar treatments, which had similar numbers of shoots to the control (Table 10). Tomato plants in plots treated with imazamox were injured and appeared to have yield loss; unfortunately, the yield data at this site was compromised by fruit theft late in season (data not shown). These results supports findings from the California crop safety and efficacy trials. Preplant incorporated sulfosulfuron and chemigated imazapic had the lowest broomrape emergence, which supports the results of the 2021 trial in Chile and is consistent with previous research (Eizenberg and Goldwasser 2018).

California Efficacy 2022

Chemigated imazamox resulted in severe injury to tomatoes in this trial. Visual injury in some plots was as high as 59% and symptoms included severe stunting, pale gray/green plants, lack of flowers, and overall vigor loss (Table 11). PPI sulfosulfuron and chemigated rimsulfuron did not cause similar crop injury. There were significant differences in broomrape emergence among treatments (Table 11). Treatment 5 (imazamox 19.2 g ai/ha) had the lowest broomrape emergence with an average of 9 clusters per 120-foot plot, while treatments 14 and 15 (acibenzolar-s-methyl 26.2, 52.4 g ai/ha, respectively) had the highest emergence at 60 and 63 clusters per plot (Table 11). Given the severe injury in imazamox-treated plots, the best treatment overall was treatment 10 (preplant incorporated sulfosulfuron paired with chemigated rimsulfuron) which had significantly lower broomrape emergence than the control treatment (Table 11). Among chemigated rimsulfuron treatments, PPI sulfosulfuron paired with chemigated rimsulfuron (Treatment 10) tended to have less broomrape emergence than chemigated rimsulfuron alone (Treatments 6, 16, 17). Foliar rimsulfuron applied three times (Treatments 7, 11) had broomrape emergence that was similar to the control plots, with an average of 58 and 53 clusters per plot (Table 11).

In the 2022 California efficacy trial, chemigated imazamox at both rates resulted in unacceptably severe injury on tomatoes. Chemigated rimsulfuron alone and paired with sulfosulfuron were safe on tomatoes and tended to have lower broomrape emergence than control treatments. In general, chemigated treatments had lower broomrape emergence than non-chemigated or control treatments. The late planted treatment (May 20) tended to have lower broomrape emergence than the control treatment (planted May 3), and although more work will need to quantify the effect of planting date on broomrape emergence, it is a promising first step.

Crop Safety

Crop injury and yield data from 2021 crop safety and 2022 efficacy studies showed significant injury resulting from chemigated imazamox. Plots in 2021 treated with chemigated imazamox had early season injury but grew out of injury symptoms and fruit yield was not reduced (Table 7). However, in the 2022 efficacy trial, chemigated imazamox resulted in significant injury with symptoms including stunting, reduced vigor, and pale green/gray stems. Injury was so severe in some plots that the trial was not harvested due to lack of fruit and scale of injury (Table 11). Chilean researchers also noted injury and yield loss in plots treated with chemigated imazamox in the first year and there were indications of similar losses in the second year (Table 9, data not shown). Tomato plants at the UC Davis site were well watered and fertilized, while plants in the California infested commercial field were well watered but less well fertilized, which may have led to the differences in injury between the two sites.

Efficacy

Given the injury from imazamox, the best treatment from both efficacy studies was PPI sulfosulfuron paired with chemigated rimsulfuron. This is very promising for California growers considering recent California Department of Pesticide Regulation approval of a 24c label for chemigated rimsulfuron following positive results from Italian research and the preliminary California efficacy trials (Anonymous 2022, Conversa et al. 2017). This means that growers with suspected or at-risk fields were able to use this treatment protocol during the 2023 season. While Israeli systems find great success with applications of ALS inhibitor herbicides sulfosulfuron and imazapic following their PICKIT decision support system, there does not seem to be a regulatory path forward for imazapic in California or Chile. Future research will not include chemigated imazamox due to the unacceptably low margin of crop safety seen in the Chilean efficacy experiments and in the California crop safety and efficacy trials. Sulfosulfuron will continue to be pursued within the USDA IR4 program for registration in California as a preplant incorporated material for branched broomrape control. In Israel, sulfosulfuron is applied both as a preplant incorporated material and as a broadcast foliar application that is incorporated with overhead irrigation (Eizenberg and Goldwasser 2018). Current California conditions do not allow for this secondary application technique, with very few fields utilizing overhead irrigation and the vast majority irrigated solely via subsurface drip irrigation. Further research in Chile will evaluate higher rates of rimsulfuron, similar to those of tested in California.

Practical Implications

This research was conducted to evaluate the crop safety and efficacy of chemigation treatments based on the PICKIT system developed in Israel (Eizenberg and Goldwasser 2018). Because of regulatory barriers to imazapic, we focused on sulfosulfuron and imazamox in trials conducted from 2021-2022 in both Chile and California. Data from these four full-season field experiments indicate that imazamox performance was not as good as reported with imazapic and unfortunately, after four seasons of research trials, it has become clear that the margin of crop safety with imazamox is insufficient. As of late 2022, California growers have an approved alternative for branched broomrape control in chemigated rimsulfuron. Ongoing research includes further development of rimsulfuron-based chemigation protocols and equipment sanitation as well as outreach to educate growers on strategies to reduce risk of spread of branched broomrape into new fields and among regions. As with any weed management program, relying on a single strategy is problematic, and future research will be dedicated to finding additional chemistries and practices to manage branched broomrape and reduce the risk of its spread throughout California tomato growing regions. Branched broomrape is of utmost concern for California tomato growers, with more infested fields being reported every year. Under its current regulatory status as an "A-listed" noxious weed requiring crop destruction, it represents the largest threat to the California tomato industry in decades. In the case of Chile, the concern is still present, since there are fewer and fewer fields not infested with branched broomrape, it will be necessary to incorporate management strategies that combine the application of chemical products with cultural practices that prevent branched broomrape seed dispersion to other fields.

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Competing Interests

The authors declare none.

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Tables

Table 1.1 Planting, harvest, growing degree targets and actual application dates for California field studies.

Application	Crop safety 2021.1	Crop safety 2021.2	Crop safety 2022.1	Crop safety 2022.2	Efficacy 2022
PPI	19-Apr	5-May	7-Apr	11-May	7-Apr
Transplant	28-Apr	12-May	13-Apr	19-May	3-May
400 GDD	20-May	4-Jun	21-May	4-Jun	26-May
500 GDD	27-May	9-Jun	26-May	14-Jun	1-Jun
600 GDD	2-Jun	15-Jun	31-May	21-Jun	6-Jun
700 GDD	7-Jun	22-Jun	3-Jun	24-Jun	12-Jun
800 GDD	10-Jun	24-Jun	8-Jun	1-Jul	16-Jun
900 GDD	16-Jun	29-Jun	14-Jun	11-Jul	23-Jun
Harvest	30-Sep	7-Oct	27-Sep	28-Sep	--

PPI: preplant incorporated, GDD: growing degree days

Table 1.2. Treatments in two 2021 chemigation crop safety studies evaluating several herbicides on tomato crop safety near Davis, CA.

	Treatment	Rate	Description	Applications
		g ai/ha		
1	Grower Standard	--	--	--
2*	Sulfosulfuron	37.5	PPI	
	Imazapic	4.8	Chem x5	400, 500, 600, 700, 800
3	Sulfosulfuron	37.5	PPI	PPI
4	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800
5	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
6	Sulfosulfuron	37.5	PPI	
	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800
7	Sulfosulfuron	37.5	PPI	
	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	
	Imazamox	28.8	Chem x5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	
	Imazamox	38.4	Chem x5	400, 500, 600, 700, 800
10	Sulfosulfuron	37.5	PPI	
	Imazamox alternate timing	9.6	Chem x5	500, 600, 700, 800, 900

*Israeli grower standard; Chem: chemigation, Foliar: foliar applied herbicide, PPI: preplant incorporated, DAT: days after transplant, GDD: growing degree days; x3/x5: three/five chemigation applications

Table 1.3. Treatments in two 2022 chemigation crop safety studies evaluating several herbicides on tomato crop safety near Davis, CA.

	Treatment	Rate	Description	Application
		g ai/ha		Growing degree days
1	California Grower Standard^	--	--	
2*	Sulfosulfuron	37.5	PPI	
	Imazapic	4.8	Chem x5	400, 500, 600, 700, 800
3	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800
4	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
5	Rimsulfuron chemigated	22.7	Chem x3	400, 600, 800
6	Rimsulfuron foliar	22.7	Foliar x3	400 , 600, 800
7	Sulfosulfuron	37.5	PPI	
7	Imazamox	9.6	Chem x3	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	
	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	
	Rimsulfuron chemigated	22.7	Chem x3	400, 600, 800
10	Sulfosulfuron	37.5	PPI	
	Rimsulfuron foliar	22.7	Foliar x3	400, 600, 800
11	Acibenzolar-S-methyl	26.2	Chem x6	400, 500, 600, 700, 800, 900
12	Acibenzolar-S-methyl	52.4	Chem x6	400, 500, 600, 700, 800, 900

^ California grower standard: 350 g ai/ha *S*-metolachlor and 91.9 g ai/ha trifluralin was applied to all plots.

*Israeli grower standard; Chem: chemigation, Foliar: foliar applied herbicide, PPI: preplant incorporated, DAT: days after transplant, GDD: growing degree days; x3/x5/x6: three/five/six chemigation applications

Table 1.4. Treatments in a 2021 efficacy study for broomrape management near Santa Cruz, Chile.

	Treatment	Rate	Description	Application
		g ai/ha		Growing degree days
1	Control	--	--	
2*	Sulfosulfuron	37.5	PPI	
	Imazapic	4.8	Chem x5	400, 500, 600, 700, 800
3	Sulfosulfuron	37.5	Foliar x3	200, 400, 600
4	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800
5	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
6	Sulfosulfuron	37.5	PPI	
	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800
7	Sulfosulfuron	37.5	PPI	
	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800
8	Sulfosulfuron	37.5	PPI	
	Imazamox	28.8	Chem x5	400, 500, 600, 700, 800
9	Sulfosulfuron	37.5	PPI	
	Imazamox	38.4	Chem x5	400, 500, 600, 700, 800

*Israeli grower standard; Chem: chemigation, Foliar: foliar applied herbicide, PPI: preplant incorporated, DAT: days after transplant, GDD: growing degree days; x3/x5: three/five chemigation applications

Table 1.5. Treatments in a 2022 efficacy study for broomrape management near Pumanque, Chile.

	Treatment	Rate	Description	Application
		g ai/ha		
1	Control	--	--	
2*	Sulfosulfuron	37.5	PPI	
	Imazapic	4.8	Chem x3	20, 35, 45 DAT
3	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800 GDD
4	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800 GDD
5	Rimsulfuron chemigated	10	Chem x3	20, 35, 45 DAT
6	Rimsulfuron foliar	10	Foliar x3	20, 35, 45 DAT
7	Sulfosulfuron	37.5	PPI	
	Imazamox	9.6	Chem x5	400, 500, 600, 700, 800 GDD
8	Sulfosulfuron	37.5	PPI	
	Imazamox	19.2	Chem x5	400, 500, 600, 700, 800 GDD
9	Sulfosulfuron	37.5	PPI	
	Rimsulfuron chemigated	10	Chem x3	20, 35, 45 DAT
10	Sulfosulfuron	37.5	PPI	
	Rimsulfuron foliar	10	Foliar x3	20, 35, 45 DAT
11	Halosulfuron	37.7	Foliar x2	

*Israeli grower standard; Chem: chemigation, Foliar: foliar applied herbicide, PPI: preplant incorporated, DAT: days after transplant, GDD: growing degree days; x3/x5: three/five chemigation applications

Table 1.6. Treatments in a 2022 efficacy study evaluating several herbicides for branched broomrape control in processing tomatoes near Woodland, CA.

	Treatment	Application	Rate	Timing	Notes
			g ai/ha		
1	Planting 1				Early May (5/3)
2	Planting 2				Late May (5/20)
3	Sulfosulfuron		37.5	PPI	Israeli Standard
		PPI			PICKIT
	Imazapic	Chem x5	4.8	400, 500, 600, 700, 800 GDD	
4	Imazamox	Chem x5	9.6	400, 500, 600, 700, 800 GDD	
5	Imazamox	Chem x5	19.2	400, 500, 600, 700, 800 GDD	
6	Rimsulfuron	Chem x3	22.7	400, 600, 800 GDD	
7	Rimsulfuron	Foliar x3	22.7	400, 600, 800 GDD	
8	Sulfosulfuron	PPI	37.5	PPI	
	Imazamox	Chem x5	9.6	400, 500, 600, 700, 800 GDD	
9	Sulfosulfuron	PPI	37.5	PPI	
	Imazamox	Chem x5	19.2	400, 500, 600, 700, 800 GDD	
10	Sulfosulfuron	PPI	37.5	PPI	
	Rimsulfuron	Chemx3	22.7	400, 600, 800 GDD	
11	Sulfosulfuron	PPI	37.5	PPI	
	Rimsulfuron	Foliar x3	22.7	400, 600, 800 GDD	
12	Sulfosulfuron	PPI	37.5	PPI	Alternate timing
	Imazamox	Chem x5	9.6	500, 600, 700, 800, 900 GDD	
13	Sulfosulfuron	PPI	37.5	PPI	Alternate timing
	Imazamox	Chem x5	19.2	500, 600, 700, 800, 900 GDD	
14	Acibenzolar-S-methyl	Chem x6	26.2	400, 500, 600, 700, 800, 900 GDD	
15	Acibenzolar-S-methyl	Chem x6	52.4	400, 500, 600, 700, 800, 900 GDD	
16	Rimsulfuron	Chem x3	12.5	400, 600, 800 GDD	
17	Rimsulfuron	Chem x3	22.7	30, 50, 70 DAT	CA 24c protocol

Chem: chemigation, Foliar: foliar applied herbicide, PPI: preplant incorporated, DAT: days after transplant, GDD: growing degree dates; x3/x5/x6: three/five/six chemigation applications

Table 1.7. Tomato yield in 2021 two chemigation crop safety studies near Davis, CA.

		---------------Experiment 1--------------			-----------Experiment 2------------------			
		40 DAT	90 DAT		48 DAT		77 DAT	
	Treatment	Injury	Injury	Yield	Injury		Injury	Yield
		%	%	kg/m^2	%		%	kg/m^2
1	Grower Standard	0	0	18.6	0	b	0	17.9
2	Sulfosulfuron/Imazapic 9.6 g ai/ha x5	0	0	21.7	10	ab	0	18.2
3	Sulfosulfuron	0	0	19.0	0	b	0	21.3
4	Imazamox 9.6 g ai/ha x5	5	0	18.1	0	b	0	20.4
5	Imazamox 19.2 g ai/ha x5	23	0	21.1	18	ab	8	16.6
6	Sulfosulfuron/Imazamox 9.6 g ai/ha x5	3	0	16.4	0	b	0	16.7
7	Sulfosulfuron/Imazamox 19.2 g ai/ha x5	8	0	20.5	10	ab	3	18.1
8	Sulfosulfuron/Imazamox 28.8 g ai/ha x5	15	0	12.9	23	ab	0	14.1
9	Sulfosulfuron/Imazamox 38.4 g ai/ha x5	25	5	19.1	35	a	13	12.7
10	Sulfosulfuron/Imazamox x5 alternate timing	3	0	19.7	0	b	0	19.5
P-value		0.13	0.22	0.69	0.01		0.21	0.24

Means with the same letter within the same column are not significantly different according to Tukey's HSD test (alpha= 0.05). DAT= days after transplant

Table 8. Tomato yield in two chemigation crop safety studies near Davis, CA in 2022.

No.	Treatment	Experiment 1 Yield	Experiment 2 Yield
		kg/m^2	kg/m^2
1	Grower Standard	19.3	15.1
2	Sulfosulfuron PPI/Imazapic x5	22.7	20.8
3	Imazamox 9.6 g ai/ha x5	21.7	15.3
4	Imazamox 19.2 g ai/ha x5	19.5	16.2
5	Rimsulfuron chemigated x3	15.8	15.9
6	Rimsulfuron foliar x3	15.5	14.2
7	Sulfosulfuron PPI/Imazamox 9.6 g ai/ha x5	17.2	17.4
8	Sulfosulfuron PPI/Imazamox 19.2 g ai/ha x5	21.4	18.9
9	Sulfosulfuron PPI/Rimsulfuron chem x3	20.1	18.7
10	Sulfosulfuron PPI/Rimsulfuron foliar x3	16.1	16.0
11	Acibenzolar-S-methyl 26.2 g ai/ha x6	16.5	18.4
12	Acibenzolar-S-methyl 52.4 g ai/ha x6	18.2	13.8
P-value		0.32	0.85

Means with the same letter within the same column are not significantly different according to Tukey's HSD test (alpha= 0.05).

Table 9. Average number of broomrape shoots per plot and tomato yield in a 2021 efficacy trial evaluating several herbicide treatments for branched broomrape control in an experiment conducted near Santa Cruz, Chile

	Treatment	Broomrape		Yield	
		Shoots/17m plot		kg/17 m plot	
1	Control	129	a	27.8	ab
2	Sulfosulfuron (37.5 g ai/ha, PPI) + imazapic (4.8 g ai/ha, chem x5)	20	bc	32.7	a
3	Sulfosulfuron (37.5 g ai/ha, PPI) + sulfosulfuron (37.5 g ai/ha, foliar x3 at 200, 400, 600 GDD)	67	abc	7.7	de
4	Imazamox (9.6 g ai/ha, chem x5)	82	ab	5.6	de
5	Imazamox (19.2 g ai/ha, chem x5)	22	bc	13.8	cd
6	Sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (9.6 g ai/ha, chem x5)	10	c	5.1	e
7	Sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (19.2 g ai/ha, chem x5)	25	bc	21.2	bc
8	Sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (28.8 g ai/ha, chem x5)	6	c	2.9	e
9	Sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (38.4 g ai/ha, chem x5)	13	c	3.2	e
P-value		<0.0001		<0.0001	

Means with the same letter within the same column are not significantly different according to Tukey's HSD test (alpha= 0.05).

Table 10. Average number of broomrape shoots per plot in a 2022 efficacy trial evaluating several herbicide treatments for branched broomrape control conducted near Pumanque, Chile

	Treatment	Broomrape Shoots/20 m plot	
1	Control treatment	407	ab
2	sulfosulfuron (37.5 g ai/ha, PPI) + imazapic (4.8 g ai/ha, chem x5)	24	b
3	Imazamox (9.6 g ai/ha, chem x5)	160	ab
4	Imazamox (19.2 g ai/ha, chem x5)	58	ab
5	Rimsulfuron (10 g ai/ha, chem x3)	290	ab
6	Rimsulfuron (10 g ai/ha, foliar x3)	710	a
7	sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (9.6 g ai/ha, chem x5)	63	ab
8	sulfosulfuron (37.5 g ai/ha, PPI) + imazamox (19.2 g ai/ha, chem x5)	36	b
9	sulfosulfuron (37.5 g ai/ha, PPI) + rimsulfuron (10 g ai/ha, chem x3)	161	ab
10	sulfosulfuron (37.5 g ai/ha, PPI) + rimsulfuron (10 g ai/ha, foliar x3)	411	ab
11	Halosulfuron, (37.7 g ai/ha, foliar x2)	309	ab
P-value		0.02	

Means with the same letter within the same column are not significantly different according to Tukey's HSD test (alpha= 0.05).

Table 11. Average number of branched broomrape clusters per 36 m plot in a 2022 efficacy trial in a heavily infested commercial tomato field near Woodland, CA.

	Treatment	Application	Rate	Broomrape Emergence		Injury	
			g ai/ha	Average # Clusters/36m row		%	
1	Planting 1			52	abc	16	bc
2	Planting 2			25	bcd	15	bc
3	Sulfosulfuron	PPI	37.5	18	cd	0	c
	Imazapic	Chem x5	4.8				
4	Imazamox	Chem x5	9.6	16	cd	46	a
5	Imazamox	Chem x5	19.2	9	d	54	a
6	Rimsulfuron	Chem x3	22.7	18	cd	1	c
7	Rimsulfuron	Foliar x3	22.7	58	ab	1	c
8	Sulfosulfuron	PPI	37.5	20	cd	45	ab
	Imazamox	Chem x5	9.6				
9	Sulfosulfuron	PPI	37.5	15	d	59	a
	Imazamox	Chem x5	19.2				
10	Sulfosulfuron	PPI	37.5	15	d	0	c
	Rimsulfuron	Chemx3	22.7				
11	Sulfosulfuron	PPI	37.5	53	abc	0	c
	Rimsulfuron	Foliar x3	22.7				
12	Sulfosulfuron	PPI	37.5	23	bcd	39	ab
	Imazamox	Chem x5	9.6				
13	Sulfosulfuron	PPI	37.5	16	cd	49	a
	Imazamox	Chem x5	19.2				
14	Acibenzolar-S-methyl	Chem x6	26.2	60	ab	0	c
15	Acibenzolar-S-methyl	Chem x6	52.4	63	a	0	c
16	Rimsulfuron	Chem x3	12.5	27	abcd	0	c
17	Rimsulfuron	Chem x3	22.7	24	bcd	0	c
P-value				<0.0001		<0.0001	

Means with the same letter are not significantly different from one another according to Tukey's HSD test (α=0.05)

Figure Legends

Figure 1.1 CO_2 pressurized chemigation system used in California trials.

Figure 1.2 Venturi injection system used for chemigation treatments in the Chilean studies.

Figures

CHAPTER 2

Adsorption of imazamox in California agricultural soils and implications for branched broomrape management

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Abstract

Studies were conducted to evaluate the safety and efficacy of chemigated imazamox for branched broomrape management in CA processing tomatoes. Across studies, there were differences in crop injury between sites: imazamox-treated tomatoes in the Davis location had minor early season injury while tomatoes at the Woodland location were severely injured or killed. The following study was conducted to investigate imazamox sorption in four California soils to determine if differences in herbicide adsorption played a role in variable crop injury observed in the field trials. To determine the sorption capacity of imazamox of each soil, a batch equilibrium study was conducted. There were significant differences in sorbed imazamox (imazamox solution 847.7 pg μL^{-1}): the clay soil had the highest adsorption (Robert's Island: 742.5 pg μL^{-1} sorbed), followed by the sandy loam soil (Ripon: 723.9 pg μL^{-1} sorbed), while the loam soils from both trial sites (Davis: 704.2 pg μL^{-1} sorbed; Woodland: 699.9 pg μL^{-1} sorbed) had the lowest adsorption and were not significantly different from one another (P=<0.0001). The results from this study illustrate only minor differences in imazamox adsorption among the soils tested which suggests that soil type was likely not a major factor contributing to differences in imazamox injury.

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KEYWORDS:

Chemigation, herbicide fate, imidazolinones, processing tomatoes, California, agriculture, parasitic plants

Introduction

Processing tomato (*Solanum lycopersicum*) is a major cash crop grown in the central San Joaquin and Sacramento valleys of California. In 2023, it was a top 10 agricultural commodity in the state worth $1.2 billion dollars [1]. Branched broomrape (*Phelipanche ramosa*) is a parasitic noxious weed that can parasitize a wide range of agricultural crops [2]. Branched broomrape is an obligate holoparasite that parasitizes a host plant's root system, reducing plant vigor [2]. Tomatoes are highly susceptible to branched broomrape and yield loss in highly infested fields can be up to 80% [3]. Branched broomrape was first noted in California in the early 1900s [4]. After an industry driven eradication program utilizing methyl bromide fumigation that began in the 1960s, it was thought to have been eradicated from California by the 1980s [5, 6]. It has reemerged in recent years, with several commercial fields having been reported since 2016 [7]. Branched broomrape is currently an A-listed pest in the state requiring crop destruct and quarantine protocols which leads to massive economic losses to affected growers [8].

Research began in 2019, to validate existing herbicide programs for broomrape management in processing tomato [9]. The programs were based on 20 years of research done by Israeli researchers for management of Egyptian broomrape (*Phelipanche aegyptiaca*) in their processing tomato systems [10]. These programs utilize acetolactate synthase (ALS) inhibitor herbicides in various combinations and application methods. There are several program regimes depending on broomrape infestation level; however, most of them utilize preplant incorporated sulfosulfuron followed by several in-season applications of imazapic applied via chemigation. Currently, neither sulfosulfuron or imazapic are labeled for use in tomatoes in California and there are differences in tomato production practices and primary broomrape species between California and Israel. Therefore, to validate and adapt the Israeli programs under California conditions and to generate the necessary data to support potential herbicide registration for this pest, a series of field studies were designed and implemented.

In 2019 and 2020, experiments focused on evaluation of preplant incorporated sulfosulfuron and chemigated imazapic for their crop safety in California tomatoes and their efficacy for branched broomrape management [9]. After two seasons of field research, it became clear that imazapic faced insurmountable barriers to registration in California, and focus shifted from imazapic to imazamox as the chemigation component. Imazamox, a sister compound to imazapic in the imidazolinones class, already has a label in California on other crops such as alfalfa, making it a better candidate for potential registration on tomatoes in California. Beginning in 2021, field studies continued the evaluation of Israeli-based herbicide programs with imazamox as the chemigation component for crop safety on tomatoes and efficacy for branched broomrape management [11].

The mechanism of action of imazamox is the inhibition of acetolactate synthase, a critical enzyme in the synthesis of branched chain amino acids [12]. Imazamox uptake occurs in both leaves and roots, and it is translocated in both the xylem and phloem [12]. It was first marketed in the United States in 1997 for use in soybeans and subsequently received a reduced risk pesticide designation due to its low mammalian toxicity and its favorable environmental fate [13]. It is widely used in the United States for postemergence control of annual broadleaf and grass weeds in agricultural and aquatic systems, including imidazolinone-resistant (IR) crop systems. In California, imazamox is registered for postemergence use in several IR crops (Clearfield/Beyond) and in alfalfa (Raptor) [14, 15]. Soil adsorption has been extensively studied in the imidazolinones herbicides, particularly those with preemergence soil activity such as imazethapyr, imazapyr, and imazaquin [16, 17, 18]. However, there are relatively few reports on imazamox soil adsorption, likely due to its primary use as a postemergence or aquatic herbicide. Among three imidazolinones evaluated, imazamox had the lowest soil sorption, followed by imazethapyr then imazaquin and that all three herbicides had lower sorption at pH 7 than at pH 5 [19]. Soil amended with biochar did not increase the sorption of any of the herbicides tested, including imazamox [20]. The authors concluded this was likely due to the fact that biochar has a net-negative charge and all herbicides tested were anionic. Another recent publication by Hu et al. [21] also evaluated imazamox adsorption in lake sediment; however, herbicide fate could be substantially different in the aerobic and irrigated environment of an agricultural field.

After two field seasons of crop safety and efficacy studies, it became clear that chemigated imazamox had the potential to cause crop injury in tomatoes at our higher rate regimes [11]. Interestingly, tomatoes at the field site near Davis, CA, had only minor early season injury in 2021 and no injury in 2022, while tomatoes at the grower field site near Woodland, CA, were severely injured in 2021 and 2022 and did not recover by the end of the season. The discrepancy in crop injury observed in plots treated with chemigated imazamox across studies and study sites led us to investigate potential contributing factors. The differences between the two trial sites included soil type, irrigation tape depth, fertility, and irrigation practices. We hypothesized that soil type differences between the two sites may have influenced the amount of plant-available imazamox and led to differences in crop injury among trial sites. To evaluate this, batch equilibrium studies were conducted in late 2022 to determine if there were differences in imazamox soil adsorption among four California soils, including soil from the two trial sites. In addition, an experiment was conducted to determine the sorption coefficient of imazamox for each soil.

Materials and Methods

Field collection

Soil was collected from four agricultural fields within the California tomato production region for batch equilibrium experiments. Collection sites included the Davis field site (38°31'48.1"N 121°47'01.1"W), a field adjacent to the Woodland field site that was not under broomrape quarantine control (38°45'29.1"N 121°46'15.0"W), a field near Ripon, CA, (37°43'03.4"N 121°12'05.0"W) to represent a sandy soil type, and a field near Roberts Island, CA (37°52'39.8"N 121°22'46.7"W) to represent a higher organic matter soil (Table 1). Soil was collected from the A-horizon in the top 7 cm, air dried, and sieved with a 2mm screen. Field capacity and bulk density of each soil were calculated. Laboratory analyses of these soils were conducted at the Colorado State University Weed Science Lab in Fort Collins, CO.

Sorption capacity

Batch equilibrium methods were used to determine the sorption capacity of imazamox in each soil [22]. A stock solution was prepared with 0.6 ppm imazamox in a 0.02 M $CaCl_2$ solution. This concentration mimicked the field rate of imazamox used in chemigation applications in field trials conducted California and Chile [11]. Five grams of air-dried soil was added to a 50 mL centrifuge tube and brought to field capacity with the imazamox solution and was allowed to sit overnight at room temperature. The next day, 5 mL of 0.02M $CaCl_2$ (aq) was added to the centrifuge tube, tubes were vortexed, then centrifuged for 10 min at 2,500 rpm (Legend X1R centrifuge, Thermo Fisher Scientific, Waltham, MA). A 2 mL aliquot of the supernatant was filtered through a 0.2 µm PVDF filter and injected into a Shimadzu 8040 LC-MS/MS system for quantification (Shimadzu Corporation, Kyoto, JP). This experiment had five 5 grams soil replications for each of 4 soils, with 20 total samples.

Herbicide soil adsorption

To determine imazamox sorption coefficients for each soil, a batch equilibrium method was used [22]. Ten grams of each soil was placed in a 50 mL centrifuge tube, followed by 10 mL of 10 μg mL^{-1} imazamox solution. The centrifuge tubes were loaded on a reciprocal shaker and shaken for 24 h at room temperature. The tubes were centrifuged at 2500 rpm for 10 min. A 2 mL aliquot of the supernatant was filtered through a 0.2 μm PVDF filter and injected into a LC-MS/MS [23]. This experiment had five replications of each soil, with 20 total samples.

The adsorption coefficient (K_d) of each soil was calculated using Equation 1 [22].

$$K = \frac{C_s^{ads}(eq)}{C_{aq}^{ads}(eq)} = \frac{m_s^{ads}(eq)}{m_{aq}^{ads}(eq)} \frac{V_0}{m_{soil}} (cm^3 g^{-1}) \tag{1}$$

Where:

$C_s^{ads}(eq) =$ *content of the substance adsorbed on the soil at adsorption equilibrium*

$C_{aq}^{ads}(eq) =$ *mass concentration of the substance in the aqueous phase at adsorption equilibrium ; this concentration is analytically determined taking into account the values given by the blanks.*

$m_s^{ads}(eq) =$ *mass of the test substance adsorbed on the soil at adsorption equilibrium*

$m_{aq}^{ads}(eq) =$ *mass of the test substance in the solution at adsorption equilibrium*

$m_{soil} =$ *quantity of the soil phase, expressed in dry mass of soil*

$V_0 =$ *initial volume of the aqueous phase in contact with the soil*

K_{oc} and F_{oc} was calculated using Equation 2 [24]

$$K_{oc} = (K_d/F_{oc}) \text{ x } 100 \qquad (2)$$

F_{oc} was calculated using Equation 3

$$F_{oc} = \text{SOM}/1.72 \qquad (3)$$

Where 1.72 is a conversion factor to estimate organic carbon from soil organic matter [24]

Quantification

Soil capacity and soil adsorption experiments were analyzed using a Shimadzu 8040 LC-MS/MS system. The LC was equipped with a C18 column (100 mm x 4.6 mm x 5µm Phenomenex Corporation, Torrance, CA) heated to 40C. A gradient mobile phase was run over an 8-min run time (Table 2). Solvent A was HPLC grade water with 0.1% formic acid and solvent B was HPLC grade acetonitrile with 0.1% formic acid. The flow rate was set to 0.4 mL min^{-1} and the injection volume was 1 µL. Under these conditions, imazamox retention time was 3.43 min. The mass spectrometer was run in positive mode with multiple reaction monitoring (MRM) optimized for imazamox analysis [23].

Soil analysis

All four soils were air dried and sieved with a 2mm screen. Two samples of each soil were sent to the UC Davis Analytical Laboratory (Davis, CA) for analysis. Soils were analyzed for physical and chemical properties including sand/silt/clay percentages, pH, cation exchange capacity (estimated), and organic matter content (loss on ignition method) (Table 1).

Statistical analysis

Final concentrations of imazamox from each soil were analyzed with a one-way analysis of variance followed by means separations using Tukey's HSD test using the agricolae package in RStudio (R version 4.1.2).

Results and discussion

There were significant differences in imazamox availability in the Ripon and Robert's Island soils when compared to Davis and Woodland soils (Figure 1). However, there was no significant difference in imazamox sorption between the Davis and Woodland soils (Figure 1). Sorbed herbicide was calculated as the difference between the initial concentration of the imazamox solution applied (847 pg μL^{-1}) and the imazamox concentration in the extracted soil solution (847 pg μL^{-1}). The greatest amount of herbicide sorption was in soil from Robert's Island (742.5 pg μL^{-1}), followed by the Ripon soil (723.9 pg μL^{-1}). The Davis and Woodland soil had similar amounts of sorption (704.2 pg μL^{-1} and 699.9 pg μL^{-1}, respectively). The organic matter content of Davis and Woodland soils was very similar (1.85% and 2.13%, respectively) and much lower than the Ripon (6.47%) and Robert's Island (4.06%) soils (Table 1). Herbicide sorption was higher in soils with greater organic matter concentrations (Table 1). Soils from the two test sites had very similar organic matter concentrations and similar levels of imazamox adsorption (Table 1, Figure 1). The pH of the Ripon and Robert's Island soils were lower (Table 1), which could have resulted in higher sorption capacity (Aichele and Penner, 2005, Hu et al., 2021).

Sorption coefficients (K_d) were higher for Robert's Island and Ripon soils, which had higher organic matter contents and higher CEC (Table 2). The Davis and Woodland site had similar K_d and K_{OC} values, likely due to their very similar soil organic matter and CEC.

These results did not support the original hypothesis that inconsistent imazamox injury between the Davis and Woodland field sites may have been related to differences in the amount of available imazamox due to soil binding characteristics. Additional factors differed between the two trial sites: the irrigation drip tape placement was between 15-25 cm at the Woodland site, below or at the low end of recommended depth for tomato production, while the Davis site was uniformly 30 cm deep [25]. The Davis field site was on a very intensively managed research farm, while the Woodland site was managed as its own 1.2-hectare subplot within a much larger 40+ hectare block with its own irrigation and fertigation system. Because of its standalone nature, the Woodland site was less intensively managed by the cooperating grower and differences in irrigation and fertilization frequency were noted. The Woodland site received less in-season fertigation applications and was irrigated more inconsistently compared to the ET_o-based irrigation schedule used at the UC Davis research farm, which has its own CIMIS weather monitoring site [26]. It is possible that non-uniform and shallow irrigation tape depth could have resulted in poor water and herbicide distribution uniformity; coupled with inconsistent irrigation and reduced post-chemigation line flush times chemigated herbicides may have been too shallow or too concentrated at the Woodland site. The deeper and more uniform irrigation tape depth and consistent irrigation sets and flush time at the Davis site could have led to better distribution uniformity of the chemigated herbicide, reducing the effective dose of imazamox to which tomato plants were exposed and leading to less serious injury [27]. Some or many of these factors could have led to differences in crop injury between the two sites and were not addressed with this research. Ultimately, due to the unacceptably low margin for safety of imazamox in this use pattern, it will not be pursued as a chemigation material from branched broomrape management in California processing tomato [11] so the precise cause of differences in tomato injury may not be determined.

Conclusion

Our results on fit within the limited existing literature on imazamox adsorption in both agricultural soils and sediment. Imazamox adsorption in sediment was dependent on the organic carbon content of sediment [21] and adsorption was more dependent on clay content than organic carbon content in Lithuanian agricultural soils [28] . In our results, K_d of imazamox among the four soils was as follows: Robert's Island > Ripon > Woodland > Davis. Robert's Island had by far the highest CEC at 30.7 meq/100g, while Davis and Woodland had the lowest at 18.0 and 18.7 meq/100g, respectively (Tables 1, 3). These results support Sakaliene et al.[28] findings that clay content impacted adsorption. Robert's Island and Ripon also had higher OM contents than Davis and Woodland, 4.06/6.47 and 1.85/2.13 respectively, which support Hu et al.'s [21] findings that imazamox adsorption was dependent on soil carbon content.

While there were statistical differences in imazamox sorption among the four soils tested, imazamox sorption in soils from the two experimental sites in Davis and Woodland were similar to one another. These results indicate that soil type likely was not a factor in the discrepancy in injury between the two trials. The low margin of crop safety observed in previous and ongoing field work for chemigated imazamox in processing tomato does not make imazamox a promising alternative as an in-season chemigation material [9, 11]. Future research will focus on refining application protocols for a recently-approved chemigation protocol for another ALS-inhibiting herbicide, rimsulfuron, and continue to evaluate other chemistries and practices for managing and reducing the spread of branched broomrape [29]. While the initial research question remains unanswered, our results add to the limited literature available on imazamox adsorption and can help to inform management decisions regarding imazamox in agricultural soils.

Acknowledgments

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Data

The data that support the findings of this study are available from the corresponding author, [MF], upon reasonable request.

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FIGURE CAPTIONS

Figure 2.1 Sorbed imazamox in four California soils. Sorbed imazamox was calculated by the following: Initial imazamox solution concentration (847.7 pg µL^{-1}) - Final soil solution concentration. Error bars represent 95% confidence intervals (P=<0.0001, n=5).

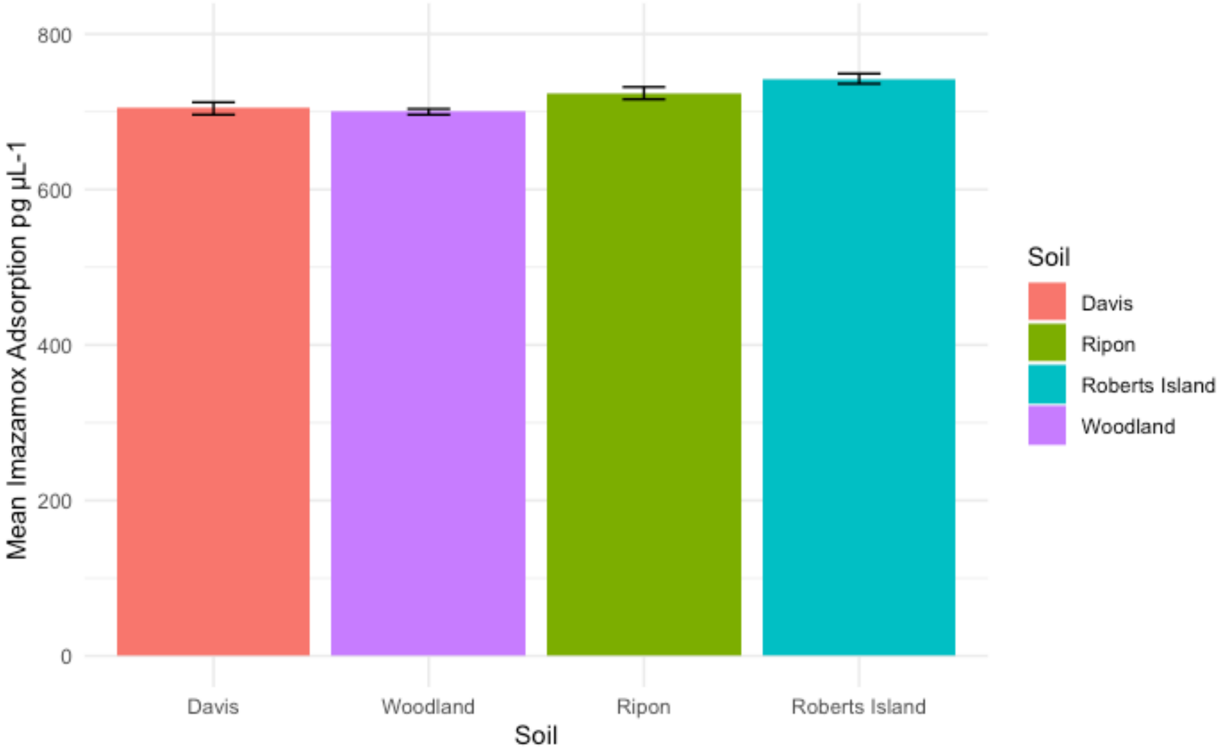

Table 2.1. Properties of soil collected from four California processing tomato fields and used in imazamox batch equilibrium experiments.

	NO3-N	Olsen-P	Na	K	Ca	Mg	CEC (estimated)	OM (LOI)	pH	Sand	Silt	Clay	Soil Class
Site	ppm			meq 100 g^{-1}				%		%			
Davis	47.7	19.0	26	553	6.35	10.11	18.0	1.85	7.40	44	36	20	Loam
Woodland	179.3	83.2	101	296	9.55	7.91	18.7	2.13	7.20	48	33	19	Loam
Ripon	320.1	129.0	69	594	10.81	3.83	16.5	6.47	6.20	75	19	6	Sandy Loam
Robert's Island	74.9	62.0	262	154	21.32	7.81	30.7	4.06	6.72	21	37	42	Clay

Table 2.2. Quantification parameters from LC-MS/MS analysis used in imazamox soil adsorption studies.

Time (min)	% Solvent A†	% Solvent B†
0	70	30
4	10	90
6	10	90
6.1	70	30
8	70	30

MRM (m/z)	Dell Time (ms)	Q1 pre-bias (V)	Collision Energy (V)	Q-3 pre-bias (v)
306.05>69.1	100	-30.0	-35.0	-24.0
306.05>261.1	100	-14.0	-24.0	-27.0
306.05>86.15	100	-30.0	-31.0	-16.0

†Solvent A consisted of water and 0.1% formic acid, solvent B consisted of acetonitrile and 0.1% formic acid.

Table 2.3. Adsorption coefficients from a 2022 study evaluating imazamox adsorption in four California agricultural soils.

	Soil type	CEC (estimated)	OM (LOI)	pH	K_d	K_{oc}
Site		meq 100 g^{-1}	%		10.0 μg mL^{-1}	10.0 μg mL^{-1}
Davis	Loam	18.0	1.85	7.40	0.21	19.89
Woodland	Loam	18.7	2.13	7.20	0.10	8.10
Ripon	Sandy loam	16.5	6.47	6.20	0.31	8.17
Robert's Island	Clay	30.7	4.06	6.72	0.43	18.20

CEC= cation exchange content, OM= organic matter

CHAPTER 3

Refining use of chemigated rimsulfuron for branched broomrape management in California processing tomato

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Abstract

Branched broomrape management is of increasing concern to California processing tomato growers. Field research was conducted in 2023 and 2024 to evaluate various application timings of chemigated rimsulfuron alone, PPI sulfosulfuron paired with chemigated rimsulfuron, as well as foliar maleic hydrazide alone and paired with PPI sulfosulfuron and chemigated rimsulfuron. In 2023, all treatments with a total of 70 g/ha rimsulfuron, alone or paired with PPI sulfosulfuron, significantly reduced broomrape emergence 77-92% compared to the nontreated control (averaging 26 clusters per 30 m plot) (P = <0.0001). In 2024, broomrape pressure was higher (average 111 clusters per 30 m plot) and all rimsulfuron treatments reduced broomrape emergence 68-86% compared to the nontreated control. Although not statistically significant, the lowest emergence was in a treatment in which the rimsulfuron applications began slightly earlier than the other chemigation treatments (P = <0.0001). In both years, five applications of foliar maleic hydrazide reduced broomrape emergence through at least midseason (P = <0.0001 vs. controls); however, in 2024 a late flush of broomrape was observed in late summer in these treatments. The 2024 experiment included a combination treatment of PPI sulfosulfuron, chemigated rimsulfuron, and foliar maleic hydrazide, which resulted in fewer than 4 broomrape clusters per 30 m plot. Overall, chemigated rimsulfuron applied at various timings and rates totaling 70 g ai/ha reduced broomrape emergence by two-thirds or more compared to the nontreated plots (P = <0.0001). No crop injury was observed in either year with rimsulfuron, sulfosulfuron, or maleic hydrazide treatments. Under a recently approved 24c label, growers can currently use three applications of rimsulfuron applied via chemigation to suppress broomrape in known infested fields or to reduce the risk of broomrape in fields of concern for this quarantine pest. Promising results from sulfosulfuron and maleic hydrazide suggest that the registration of additional herbicides could help develop even more robust branched broomrape management programs.

Nomenclature

Rimsulfuron, sulfosulfuron, branched broomrape, *Phelipanche ramosa* L., tomato, *Solanum lycospersicum* L.

Keywords

Herbigation, chemigation, ALS inhibitors, parasitic plants, quarantine pest

Introduction

Processing tomato is a major cash crop in the Sacramento and San Joaquin Valleys of California and is among the top 10 crops by farm gate value in the state, worth over one billion USD per year (USDA NASS, 2023). California produces around 30% of the worldwide processing tomato crop, with over 11.5 million mT produced in 2023, with an average yield of over 113 mT per hectare (WPTC 2023, USDA NASS). Other top processing tomato producers include China (8 million mT), Italy (5.4 million mT), Spain (2.6 million mT), and Portugal (1.5 million mT) (WPTC 2023). In South America, Chile is the largest producer at 680,000 mT of tomatoes produced in 2023 (Oficina de Agrarias, 2023). California processing tomatoes are grown in a highly managed cropping system where they are mechanically transplanted, intensively managed with fertilizer and pesticide programs, and mechanically harvested (Geissler and Horwath, 2016).

Broomrapes *(Orobanche and Phelipanche* spp.*)* are parasitic plants that are native to the Mediterranean basin (Parker and Riches, 1993). Broomrapes are achlorophyllic holoparasites that gain all of their nutrients from a host plant's root system (Parker 2008; Joel 2009). Some broomrape species have narrow host ranges, while others, such as branched broomrape *(Phelipanche ramosa)* and Egyptian broomrape *(Phelipanche aegyptiaca)*, have wide host ranges that include many agricultural crop families grown in California including crop plants from the Alliaceae, Asteraceae, Brassicaceae, Cannabaceae, Cucurbitaceae, Fabaceae, and Solanaceae families (Parker and Riches 1993). Among the Solanaceous crops, tomatoes are highly susceptible to parasitism by branched broomrape (Osipitan et al. 2021).

Broomrapes respond to specialized chemical signals known as strigolactones exuded from their host plants to initiate germination (Parker 2008). After receiving the strigolactone signal, broomrape seeds will germinate and produce a small radicle that attaches to a host plant's root. After successful attachment, a tubercle forms, and upon full development, sends shoots above the soil surface.

In California, two species of *Phelipanche* have been reported: branched and Egyptian broomrape. Branched broomrape has been present in the state since the early 1900s, though it was thought to have been eradicated by the late 1980s after a coordinated effort by industry and state stakeholders (Gaimari and O'Donnell 2008; Jain and Foy 1989). However, in recent years it has been reported in numerous commercial fields in the Sacramento Valley (Osipitan et al. 2021). Egyptian broomrape has only been reported in three fields in the United States, all in the Sacramento Valley of California and is currently thought to be eradicated after fumigation of those fields (Miyao 2017). Branched broomrape is an "A-listed" quarantine pest in California requiring crop destruction if found and reported in a commercial field (Kelch, 2017). The resurgence of branched broomrape presents a major threat to both regional and statewide production due to its regulatory status (Kelch 2017; Osipitan et al. 2021). In addition to the loss of the crop in the reporting year, a hold order is placed which bars the planting of host crops for several more years, presenting affected growers with a massive cumulative economic loss (Miyao 2017).

Many species of broomrapes are widespread throughout crop production areas in Mediterranean climates and present major difficulty to growers. Through decades of applied research, researchers in Israel developed a decision support system and treatment protocols for management of Egyptian and branched broomrapes in their processing tomato systems (Hershenhorn et al. 1998; Eizenberg et al. 2004; Hershenhorn et al. 2009; Eizenberg and Goldwasser 2018). The "PICKIT" decision support system relies on a thermal time model (growing degree days) to predict broomrape phenological stages and, based on these predictions, ALS inhibitor herbicides are applied at very low rates at times intended to target specific broomrape life stages and attachment to the host crop (Ephrath et al. 2012; Eizenberg, et al. 2012). The PICKIT system includes several regimes that depend upon broomrape infestation levels, with most protocols based on preplant incorporated or water incorporated sulfosulfuron followed by multiple applications of chemigated imazapic.

In California, research began in 2020 to validate and generate registration support data for several herbicides used in the PICKIT regimes (Fatino and Hanson 2022, Fatino et al. 2024). After two seasons, it became clear that there were significant regulatory barriers to registering imazapic in California and research pivoted to imazamox which is registered in the state (Anonymous 2022a). However, field studies with chemigated imazamox in 2020-21 in California and Chile indicated that the margin of safety of chemigated imazamox was insufficient on processing tomatoes (Fatino et al. 2024).

In 2022, rimsulfuron was also evaluated as a foliar and chemigation treatment following success in reducing broomrape emergence in Israeli and Italian processing tomato systems (Eizenberg and Goldwasser, 2018; Conversa, et al. 2017). In Israel, rimsulfuron was evaluated as postemergence treatment incorporated with overhead irrigation (Eizenberg and Goldwasser, 2018). Israeli results from rimsulfuron incoporated with irrigation were good, but not as successful as sulfosulfuron, which would later become the basis of the PICKIT system (Eizenberg and Goldwasser, 2018). In Italy, rimsulfuron applied three times via chemigation through surface drip irrigation was successful in reducing broomrape emergence (Conversa et al. 2017). These results and other research would eventually lead to chemigated rimsulfuron being labeled in Italy for branched broomrape control (DuPont Executive).

In the United States and many other global markets, the plant growth regulator maleic hydrazide is commercially used as a sprouting inhibitor in onions, garlic, shallots, and potatoes (Venezian et al. 2017; Anonymous 2024). Israeli researchers also evaluted maleic hydrazide (MH) for Egyptian broomrape control in processing tomato (Venizian et al. 2017). Venezian et al. (2017) reported that MH had a slight inhibitory effect on broomrape germination and that it greatly inhibited early development stages in laboratory studies. These results indicated that initial attachment and establishment of tubercles in the host root tissue are the main developmental stages inhibited by MH. In field studies, they reported that sequential foliar applications of MH reduced broomrape emergence in processing tomatoes but that sequential chemigated applications were not as successful in reducing broommrape emergence and that some treatments had negative effects on yield (Venezian et al. 2017).

Rimsulfuron is widely used in California processing tomato production as a preemergence or foliar selective broadleaf herbicide but was not registered for application via chemigation. After the chemigation label was approved in late 2022 in California tomatoes (Anonymous 2022b), further research was conducted in 2023 and 2024 to validate the performance for branched broomrape management and to refine application timings and techniques. In addition, research was conducted to validate two protocols utilizing maleic hydrazide for branched broomrape management and to develop support data for potential future registration.

Materials and Methods

Field trials were conducted during 2023 and 2024 in a commercial tomato field near Woodland, CA, (38°45'29.1"N 121°46'15.0"W). This field was first reported to be infested with branched broomrape in 2019 and a high broomrape population has been well documented in subsequent efficacy studies (Fatino and Hanson 2022).

The soil composition at this site was 48% sand, 33% silt, and 19% clay with an organic matter content of 2.13% and a pH of 7.20. The field site was set up with raised 1.5 m beds with a single 22 mm drip line buried 20-25 cm deep in the center of the bed with 0.6 L hr^{-1} emitters spaced every 30 cm. Individual plots were 30 m long and arranged in a randomized complete block design with four replications.

Treatments focused on evaluations of sulfosulfuron, rimsulfuron, and maleic hydrazide alone and in combination with one another at several timings (Tables 2, 3). Preplant incorporated (PPI) and foliar herbicides were applied using a CO_2 backpack sprayer with a three-nozzle boom delivering 187 L ha^{-1} with TeeJet AIXR 11002 nozzles and were mechanically incorporated with a power incorporator and bed shaper after application. 'HM 58841' tomato transplants were mechanically transplanted with 30 cm in-row spacing in a single-line. Chemigation applications were made to single bed plots during an irrigation set by connecting a CO_2-pressurized 3L bottle of herbicide solution between the supply line and buried drip line and injecting the mixture over 10-15 minutes. The irrigation set continued for approximately 1 hr after the chemigation treatment to flush lines and distribute the herbicide into the tomato root zone.

The 2023 trial focused on slight modifications of the rimsulfuron application schedules. Chemigation and foliar applications were made according to a growing degree day schedule (Eizenberg and Goldwasser, 2018) or a simplified days after transplanting schedule (DATP, Tables 1 & 2). These treatments were applied as rimsulfuron alone or in combination with PPI sulfosulfuron. The annual maximum use rate for foliar or chemigated rimsulfuron in California is 70 g ai/ha; the 24C SLN calls for three applications of 23.3 g ai/ha to utilize the maximum annual use rate (Anonymous 2022b). A secondary goal in 2023 was to evaluate GDD and DATP protocols in which this annual maximum amount was split into four treatments of 17.4 g ai/ha: one foliar application for non-broomrape broadleaf weed control and three chemigated applications for broomrape control. Lastly, maleic hydrazide was applied according to two protocols described by Venezian et al. (2017): a constant rate protocol with five applications of 400 g ai/ha and a split rate protocol with two applications of 270 g ai/ha followed by three applications of 540 g ai/ha.

The 2024 trial continued to evaluate chemigated rimsulfuron alone and paired with sulfosulfuron, as well as foliar maleic hydrazide alone and paired with sulfosulfuron and rimsulfuron, applied according to both GDD and DATP schedules as described above and in Tables 1 and 3. In 2024, the annual max rate of rimsulfuron was split into three chemigated applications of 23.3 g ai/ha per the 24C label, one foliar application and three chemigated applications of 17.4 g ai/ha, and five chemigated applications of 13.9 g ai/ha. Additionally, to generate data relevant to tomato markets in Chile, the annual maximum rate of rimsulfuron in Chile was split into three chemigated applications of 10 g ai/ha. Collaborators at UC Davis Chile have worked with UC Davis researchers in the past to develop herbicide programs for their tomato systems, which have significantly higher populations of branched broomrape than those in California (Fatino et al. 2024). This trial also included, for the first time, a chemigated sulfosulfuron treatment for comparison to the PPI treatment and to chemigated rimsulfuron.

Data collection and analysis

In both experiments, broomrape emergence was monitored weekly and clusters of emerged shoots were marked with wire construction flags (Fig. 1). The trials were terminated at commercial tomato maturity and the number of flags in each plot were recorded. Data were analyzed with a one-way analysis of variance followed by a Tukey-HSD test in RStudio version 1.2.5033.

Results and Discussion

2023. There was no tomato crop injury observed in any of the treated plots (data not shown). All treatments reduced broomrape emergence compared to the nontreated controls but there were no significant differences among treatments (Table 2). The nontreated control plots had the highest broomrape emergence with 26 clusters per 30 m plot on average, while treatment 7 (sulfosulfuron + rimsulfuron x3 GDD) had the lowest emergence at 2 clusters per plot on average (Table 2). Although there were no significant differences in broomrape emergence among treatment timing regimes, treatments applied according to the growing degree day schedule tended to have slightly lower broomrape emergence. The growing degree day schedule had the second and third chemigation applications applied earlier than the DATP schedule (Table 1) which may have contributed to the numerical difference observed. Based on this observation, the DATP treatments were adjusted to 20, 30, 40 DATP instead of 30, 50, 70 DATP in 2024. Both the split rate maleic hydrazide protocol and the constant rate protocol resulted in similar levels of broomrape emergence with 5 and 4 clusters per plot on average (Table 2).

2024. There was no tomato crop injury observed in any of the treated plots (data not shown). Broomrape emergence was much higher in 2024 than in 2023, with 111 versus 24 clusters per plot in the nontreated controls, respectively (Tables 2, 3). Most treatments reduced broomrape emergence compared to the nontreated control; the only treatments that did not reduce cumulative broomrape emergence were preplant incorporated sulfosulfuron alone and the constant rate foliar maleic hydrazide (Treatments 8, 10; Table 3). Interestingly, the preplant incorporated sulfosulfuron treatment had slow but steady broomrape emergence as seen in the control plots while the MH treatment had extremely low broomrape emergence until about 5 weeks after the last treatment (data not shown). While there were no significant differences in broomrape emergence among the other treatments, the treatment with the lowest broomrape emergence was the full stack treatment (Treatment 12) with 4 clusters per plot on average (Table 3).

After two field seasons of efficacy trials, it is clear that 70 g ai/ha of chemigated rimsulfuron is effective in reducing broomrape emergence compared to nontreated controls. Preplant incorporated sulfosulfuron results were mixed: in 2023 this treatment reduced emergence significantly compared to the nontreated control but in 2024 was not effective alone but appeared to be beneficial in combination with chemigated rimsulfuron and foliar maleic hydrazide. Foliar maleic hydrazide provided variable results: in 2023 both protocols reduced emergence compared to control, and in 2024 there was very good broomrape suppression until mid-July when a flush of emergence reduced the cumulative efficacy of both protocols. Further research could focus on different timings of this treatment to potentially extend the excellent early season control seen in the 2024 trials. The full stack treatment of PPI sulfosulfuron, chemigated rimsulfuron, and foliar maleic hydrazide provided 96% reduction in broomrape emergence in 2024. This was the best treatment by far, and further research will continue to evaluate these chemistries and generate additional data to support potential registration for their use in California tomatoes.

In 2024, the GDD schedule was applied earlier than the early DATP schedule and had numerically lower emergence than both the early (Treatment 6) and late (Treatment 7) DATP treatments (Table 3). Moving forward, a more simple DATP-based schedule of three applications applied every 10 days between 20 to 50 DATP will be recommended to growers. This recommendation more closely follows the Italian Executive label (DuPont Executive). Future research will continue to evaluate chemigated sulfosulfuron, which significantly reduced broomrape emergence in 2024 . This material is widely used in Israel where is a foliar application is incorporated with overhead irrigation (Eizenberg and Goldwasser, 2018); however, this is not very feasible in California, where the vast majority of tomato fields are irrigated solely with subsurface drip irrigation. However, applying sulfosulfuron as a chemigated treatment may be a way to achieve similar control to the Israeli treatments within the confines of California agronomic practices. Under the current 24C label for chemigated rimsulfuron, the full annual maximum rate is split into three chemigation treatments, leaving none available for broadleaf weed control (Anonymous 2022b). The use of chemigated sulfosulfuron as a portion of the broomrape management program could allow some portion of the allowable annual use of rimsulfuron to be used as a foliar treatment for broadleaf weed control, particularly for selective control of nightshades (*Solanum spp.*). Treatment 3 also aimed to address this drawback, with one foliar application for broadleaf weed control and three for broomrape control. It performed similarly to other rimsulfuron treatments, and had numerically lower emergence than treatment 2 with three chemigated applications (Table 3).

Practical Implications

In late 2022, the California tomato industry successfully acquired a 24c SLN for chemigated rimsulfuron (Anonymous 2022b). This registered 24c protocol effectively reduced broomrape emergence upwards of 70% in the relatively low levels of infestation currently present in California (Table 3). There is some evidence that the more complicated GDD-based protocol may be slightly more effective than the DATP-based protocol; however there were no statistical differences between the two timing protocols and current recommendations are not changed. There is some evidence to suggest that starting chemigation treatments ten days earlier (20, 30, 40 DATP vs 30, 50, 70 DATP) and more numerous applications of lower doses of rimsulfuron may improve efficacy, but these results should be validated with further research and surveys.

While none of treatments evaluated reach eradication levels and may not be sufficiently effective in a highly infested field due to the regulatory status of branched broomrape, rimsulfuron-based protocols are likely to provide significant risk-reduction benefit in fields with low infestations or in fields that are at risk of seed introduction but currently not known to be infested. Due to the unique status of branched broomrape and unconventional application method, substantial outreach efforts have been and are continuing to be made to educate growers and pest managers on chemigation protocols, strategies, and benefits of utilizing chemigated rimsulfuron for branched broomrape management.

Results from these experiments have been shared with researchers and tomato industry professionals in Chile to facilitate future research there and for the potential registration of chemigated rimsulfuron in their tomato systems. Researchers there plan to evaluate a similar protocol in commercial fields, which have significantly higher infestations than those in California. Results from the 2024 full stack treatment indicate high levels of efficacy (96% reduction in broomrape emergence) and are very promising for future broomrape management in California but will require a substantial amount of additional research to generate registration support data.

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Competing Interests

The authors declare none.

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Tables

Table 3.1. Application dates from two branched broomrape efficacy trials conducted near Woodland, CA

Treatment		2023	2024
Preplant incorporated	Preplant incorporated	5-May	28-March
-	Transplant	21-May	9-Apr
Chemigation	400 GDD	12-June	9-May
Chemigation	600 GDD	20-June	16-May
Chemigation	800 GDD	30-June	30-May
Chemigation	1000 GDD	-	6-June
Chemigation	20 DATP	-	3-May
Chemigation	30 DATP	14-June	9-May
Chemigation	40 DATP	-	20-May
Chemigation	50 DATP	11-July	30-May
Chemigation	70 DATP	5-Aug	6-June
Foliar MH, rimsulfuron	100 GDD	31-May	22-Apr
Foliar MH	200 GDD	5-June	27-Apr
Foliar MH	400 GDD	12-June	9-May
Foliar MH	700 GDD	23-June	28-May
Foliar MH	1000 GDD	5-July	6-June

GDD: growing degree days, DATP: days after transplant, MH: maleic hydrazide

Table 3.2. Treatments from a 2023 broomrape efficacy study conducted near Woodland, CA.

Treatment		**Active Ingredient**	**Rate**	**Application**	**Timing**	**Broomrape emergence**	
			g ai/ha			Clusters/30m	
1	Control 1					28	a
2	Control 2					24	a
3	Sulf solo	Sulfosulfuron	37.5	PPI		8	b
4	Rim solo 4x GDD	Rimsulfuron	17.4	Foliar x1; Chem x3	100 (F), 400, 600, 800 GDD	5	b
5	Rim solo 4x DATP	Rimsulfuron	17.4	Foliar x1, Chem x3	100 GDD (F), 30, 50, 70 DATP	5	b
6	Sulf+Rim 4x GDD	Sulfosulfuron	37.5	PPI		3	b
6		Rimsulfuron	17.4	Foliar x1; Chem x3	100 (F), 400, 600, 800 GDD		
7	Sulf+Rim 3x GDD	Sulfosulfuron	37.5	PPI		2	b
7		Rimsulfuron	23.2	Chem x3	400, 600, 800 GDD		
8	Sulf+Rim 3x DATP	Sulfosulfuron	37.5	PPI		6	b
8		Rimsulfuron	23.2	Chem x3	30, 50, 70 DATP		
9	MH constant rate	Maleic hydrazide	400 x5	Foliar x5	100, 200, 400, 700, 1000 GDD	5	b
10	MH split rate	Maleic hydrazide	270 x2, 540 x3	Foliar x5	100, 200, 400, 700, 1000 GDD	4	b
P-value						<0.0001	

PPI: preplant incorporated, Chem: chemigated, GDD: growing degree days, DATP: days after transplant; MH: maleic hydrazide; Sulf: sulfosulfuron, Rim: rimsulfuron

Table 3.3. Treatments from a 2024 broomrape efficacy study conducted near Woodland, CA.

	Treatment	Active Ingredient	Rate g ai/ha	Application	Timing	Broomrape Emergence	
			g ai/ha			Clusters/30 m	
1	Control 1					111	ab
2	Rimsulfuron x3	Rimsulfuron	23.2	Chem x3	400, 600, 800 GDD	36	c
3	Rimsulfuron x4	Rimsulfuron	17.4	Foliar, Chem x3	200 (F), 400, 600, 800 GDD	25	c
4	Rimsulfuron x5	Rimsulfuron	13.9	Chem x5	200, 400, 600, 800, 1000 GDD	15	c
5	Sulf+Rim x3 GDD	Sulfosulfuron	37.5	PPI		18	c
5		Rimsulfuron	23.2	Chem x3	400, 600, 800 GDD		
6	Sulf+Rim x3 DATP	Sulfosulfuron	37.5	PPI		34	c
6		Rimsulfuron	23.2	Chem x3	25, 35, 45 DATP		
7	Sulf+Rim Late DATP	Sulfosulfuron	37.5	PPI		32	c
7		Rimsulfuron	23.2	Chem x3	30, 50, 70 DATP		
8	Sulfosulfuron alone	Sulfosulfuron	37.5	PPI		114	a
9	Sulfosulfuron drip	Sulfosulfuron	12.5	Chem x3	400, 600, 800 GDD	16	c
10	MH constant rate	Maleic hydrazide	400 x5	Foliar x5	100, 200, 400, 700, 1000 GDD	44	bc
11	MH split rate	Maleic hydrazide	270 x2, 540 x3	Foliar x5	100, 200, 400, 700, 1000 GDD	27	c
12	Full stack	Sulfosulfuron	37.5	PPI			
12		Rimsulfuron	23.2	Chem x3	400, 600, 800 GDD		
12		Maleic hydrazide	270 x2, 540 x3	Foliar x5	100, 200, 400, 700, 1000 GDD	4	c
13	Rim Chile rate	Rimsulfuron	10	Chem x3	400, 600, 800 GDD	40	c
P-value						<0.0001	

PPI: preplant incorporated, Chem: chemigated, GDD: growing degree days, DATP: days after transplant, sulf: sulfosulfuron, rim: rimsulfuron MH: maleic hydrazide

Figures

Figure 3.1 Colored flags in a 2024 field trial near Woodland, CA, marking broomrape emergence over time in a nontreated control plot (left) and 23.3 g ai/ha x3 chemigated rimsulfuron treated plot (right) approximately 110 days after transplant.

CHAPTER 4

Evaluating potential for integrated broomrape management: variations in commercial cultivar resistance to broomrape and effect of planting date

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Abstract

Branched broomrape (BR) is of growing concern to the California tomato industry, with integrated management strategies needed to reduce the impact of the current infestation and mitigate the spread of this highly-regulated parasitic weed among fields. Herbicide efficacy research was conducted in 2020 and 2021 in a field known to be highly infested with branched broomrape; however, during the 2021 experiment no broomrape emerged in any plots. Because tomato cultivars and planting dates differed between the two years, several experiments were conducted to evaluate the impact of cultivar and transplant date on broomrape parasitism in processing tomato. The 2021 field was planted to a different cultivar (‘SVTM 9024’) and planted 10 weeks later than 2020; this suggested the hypothesis that cultivar and/or planting date could influence broomrape emergence. Variations in resistance were evaluated in 2022 greenhouse study of 20 cultivars, including ‘SVTM 9024’ planted in the 2021 trial, and continued in 2023 and 2024 to evaluate broomrape host status and temporal differences in broomrape emergence. In the broomrape-infested field site, several commercial processing tomato cultivars and grafted combinations were evaluated during 2022, 2023, and 2024. Additionally, two planting date studies were conducted in 2022 and 2024 in the field to evaluate the effects of delayed tomato transplanting on broomrape emergence. Results from the 2022 greenhouse screening indicated that all cultivars, including ‘SVTM 9024’, were susceptible to broomrape parasitism, but that there could be variation in temporal emergence. The 2023 greenhouse studies confirmed this, with significant variation in the timing of broomrape emergence between ‘SVTM 9025’ and ‘H9553’ (P=0.05). The 2024 greenhouse study conducted in mid-summer had no emergence in any of the cultivars, likely due to hot conditions in the greenhouse leading to secondary dormancy of the preconditioned seed. Field cultivar studies conducted in 2023 and 2024 showed no significant differences in BR emergence among conventional or grafted cultivar combinations (P = 0.23, 0.74); results for the non-grafted cultivars were consistent with greenhouse studies. Broomrape was significantly reduced by later planting dates in the 2024 trial (P = <0.001), with no emergence at the latest planting date (June 10, 2024); 2022 planting date study was

consistent with these results, with a 52% reduction on emergence at the later date, although differences were not significant (P = 0.21). Taken together, these experiments suggest that there is some variation in resistance among the tested commercial cultivars and delayed transplanting seems to reduce BR emergence and future research will seek to confirm this.

Introduction

Processing tomatoes (*Solanum lycospersicum*) are a major cash crop in California, and rank among the top 10 agricultural commodities in the state by farm gate value each year (USDA NASS 2023). California produces around 30% of the worldwide processing tomato crop, with over 11.5 million mT produced in 2023; other top processing tomato producers include China (8 million mT), Italy (5.4 million mT), Spain (2.6 million mT), and Portugal (1.5 million mT) (WPTC 2023). California processing tomatoes are grown in a very intensive cropping system where they are mechanically transplanted, intensively managed with fertilizer and pesticide programs, and mechanically harvested. Processing tomato genetics have greatly improved in recent decades, with 2023 yields averaging 114 mT per hectare, more than double the yields from 50 years ago (Barrios-Masias and Jackson 2014). Breeding programs have historically focused on traits related to yield and soilborne pathogen resistance, including resistance to parasitic plants such as dodder (*Cuscuta spp.*). However, with the recent resurgence of the parasitic weed branched broomrape (*Phelipanche ramosa*), there has been growing interest in resistance to this pest, whose population within Yolo County in the Sacramento Valley has been growing in recent years (Osipitan et al. 2021). Two species of broomrape have been reported in California: branched broomrape has been present in the state since the early 1900s, though it was thought to have been eradicated by the late 1980s after a coordinated effort by industry and state stakeholders (Gaimari and O'Donnell 2008; Jain and Foy 1989). Egyptian broomrape (*Phelipanche aegyptiaca*) has only been reported in three fields in California, and is currently thought to be eradicated after fumigation of those fields (Miyao 2017).

Broomrapes (*Orobanche* and *Phelipanche* spp.) are parasitic plants that are native to the Mediterranean basin (Parker and Riches, 1993). Broomrapes are achlorophyllic holoparasites that gain all of their nutrients from a host plant's root system (Parker 2008; Joel 2009). There are many broomrape species that parasitize crop plants; however, two are especially virulent and widespread in agricultural systems throughout the world: branched broomrape and Egyptian broomrape. Host specificity varies among broomrape species, with branched broomrape having a wide host range including crop plants from the Alliaceae, Asteraceae, Brassicaceae, Cannabinaceae, Cucurbitaceae, Fabaceae, and Solanaceae families (Parker and Riches 1993). Among the Solanaceous crops, tomatoes prove to be highly susceptible to parasitism by branched broomrape (Osipitan et al. 2021).

Broomrapes utilize specialized chemical signals from their host plants to initiate germination; these signals are phytohormones known as strigolactones (Fernandez-Aparicio et al.). Strigolactones (SLs) are exuded from plant roots and are involved in the development of symbiotic relations with arbuscular mycorrhizae and also related to plant stress response (Boyno et al. 2023). After receiving a SL signal from a host plant, broomrape seeds will germinate and produce a small radicle that attaches to the host plant's root. After successful attachment, a tubercle will form, swell, and develop on the host root (Parker 2008). Upon full development, shoots will grow from the tubercle and after reaching the soil surface, these shoots flower shortly after emergence and produce thousands of minute seed that can survive decades in the soil seedbank (Parker 2008).

Broomrape is common in many agricultural regions with Mediterranean climates, and researchers in Israel have spent decades developing herbicide programs for management of broomrape in their processing tomato systems (Eizenberg and Goldwasser, 2018). Recent research in California has worked to validate and expand upon the decades of research conducted in Israel to meet the growing concern of branched broomrape in California tomato seasons. This research focused on validating and eventually modifying herbicide programs to manage branched broomrape via chemical control methods (Fatino and Hanson 2022, Fatino et al. 2024). Several herbicide programs proved rather effective, and one has been approved for use in California tomatoes (Anonymous 2023). However, while finally having an approved management tool is helpful to growers, developing additional tactics and approaches is necessary to effectively manage and reduce the spread of this pest. With only one herbicide mode of action approved for broomrape management in California, the stewardship of this approved chemistry is a high priority among growers and researchers. To further develop an integrated management program, several studies evaluating cultural control methods were conducted between 2021 and 2024 in California.

In 2021, an efficacy study was conducted in a commercial field known to be infested with branched broomrape since 2019 (Fatino and Hanson, 2022). Due to logistical constraints related to an unusually wet spring, the field was planted very late for the region, and immediately following transplant, the region experienced a heat wave with temperature over 40 degrees C for 10 days. Herbicide applications were made, and the field was monitored for branched broomrape emergence throughout the rest of the growing season. Although this field was highly infested in the two previous years of tomato, during the 2021 growing season, not a single broomrape plant was found in the 1.5-hectare experimental site. This led to several hypotheses as to the lack of emergence in the 2021 growing season including possible happenstance resistance in the planted cultivar and delayed planting date reducing or eliminating emergence. The objective of the following experiments were to determine if the tomato cultivar planted in the trial, 'SVTM 9024', was susceptible to branched broomrape, and to determine if the later-than-normal planting date could have contributed to the lack of branched broomrape emergence.

Materials and Methods

Variations in resistance across cultivars

Greenhouse pilot study 2022

After the lack of broomrape emergence during field trials during the summer growing season, a screening study was initiated in the fall of 2021. The objective of this study was to screen the top commercial tomato cultivars in California for happenstance resistance to branched broomrape, even though this has not been a specific breeding objective for the industry previously. The top 20 cultivars by planted acreage were selected from the 2021 Processing Tomato Advisory Board publication (Table 1; PTAB 2021). Seed from each of these cultivars were obtained from a local seed distributor (AgSeeds Unlimited, Woodland, CA) and planted into 1.25 cm x 1.25 transplant plug trays in the Contained Research Facility (CRF) greenhouse at UC Davis. Broomrape seeds require a preconditioning phase with specific environmental conditions (Murdoch and Kebreab, 2013). To precondition seed in the pilot study, broomrape seed was placed in petri dishes on wetted Whatman paper, sealed with Parafilm, and shallowly buried in pots filled with moistened soil in the greenhouse. These conditions aimed to mimic a warm moist soil environment that favors broomrape preconditioning (Murdoch and Kebreab, 2013). When tomatoes reached commercial transplant size (15-20 cm), plants were removed from the plug trays and transplanted into 3.785 L pots. Before planting, the root ball of the tomato seedling was inoculated with preconditioned broomrape seed. The study was arranged in a randomized complete block design with three replications of each cultivar treatment. Pots were monitored and broomrape emergence recorded twice weekly. The study was terminated 102 days after transplant after broomrape emergence had been observed in all pots.

2023 Greenhouse screening study

Following successful results from the 2021/22 pilot study, another greenhouse study was initiated in December of 2021 to screen additional commercial cultivar and precommercial lines and to evaluate temporal differences in broomrape emergence among the same cultivars. The previously described 20 cultivars from 2021 PTAB list were planted, along with 5 additional cultivars that industry partners were interested in screening (Table 1). This study included the cultivar SVTM 9024, which was the planted cultivar in the original 2021 field trial where no BR emergence was observed. This study followed the same methods as described in the 2021/22 pilot study and was arranged in a randomized complete block design with three replications of each treatment cultivar. A data logger recording soil temperature and moisture was placed in a pot from the study determine the cumulative growing degree days at broomrape emergence among each cultivar and to provide data for future modelling of broomrape emergence in greenhouse and field studies. Pots were monitored and broomrape emergence recorded twice weekly. The study was terminated at 89 days after transplanting after emergence had been noted in all pots.

2024 Greenhouse screening study

Following updated permit conditions for branched broomrape research in early 2024, another round of the screening study was initiated in late spring in a non-CRF greenhouse. Tomatoes were seeded on May 7, 2024, and inoculated with preconditioned broomrape seed and transplanted into 1 L pots on June 5, 2024. This study was arranged in a randomized complete block design with three replications. A data logger was placed in a pot from the study and broomrape emergence was monitored and recorded twice weekly.

2022 Field cultivar study

In this trial, four commercial cultivars were evaluated, including three grafted combinations, 1 ungrafted control, as well as two ungrafted rootstocks (Table 2). The grafted plants were provided by The Morning Star Company, a California tomato processor that is invested in tomato grafting technology. The cultivar combinations used were chosen for their soilborne disease resistance packages, rather than because of specific information about broomrape susceptibility. Variations in resistance was evaluated based broomrape emergence (Table 2). Due to delays in receiving the grafted plant material, this study was hand planted on June 6, 2022, which is relatively late for this region. Plots consisted of 5 m sections of each combination planted on a single 1.5 m wide bed and each cultivar treatment was replicated four times on separate beds.

2023 Field cultivar study

In spring of 2023, a field study evaluating several of the most-planted cultivars in Yolo County for variation in broomrape sensitivity was initiated. This study evaluated ‘HM 8237’, ‘SVTM 9016’, and ‘SVTM 9019’ in a randomized complete block design with eight replications. In addition to this, ‘H9553’ was compared to ‘HM58841’ in an unreplicated demonstration at the same trial site. These cultivars were mechanically transplanted with a 3-row planter on May 21, 2023, in a single plant-line per bed with 30 cm plant spacing. Each plot consisted of a 30 m long x 1.5 m bed.

2024 Field cultivar study

In spring of 2024, a field study was conducted to evaluate three grafted cultivar combinations in the Yolo County broomrape-infested field site. This study included the following combinations: H1996 x CG6094, H1996 x CG4069, and H1996 x CG6575. The grafted plants were provided by The Morning Star Company. As in the 2022 study, the cultivar combinations were chosen for their soilborne disease resistance packages. The study was arranged in a randomized complete block design with five replications. Each plot consisted of a 36 m long x 1.5 m bed. The plants were mechanically transplanted with a 3-row planter on April 9, 2024, in a single-line with 60 cm spacing (standard wider spacing for grafted plants).

Data analysis

Data were analyzed using a one-way analysis of variance followed by a Tukey-HSD test in RStudio version 1.2.5033.

Planting date studies

2022 Planting date study

In the planting date experiment, two transplant dates were evaluated, May 3 and May 20, 2022. The trial was arranged in a randomized complete block design with four replications. Each plot consisted of a 30 m long x 1.5 m bed. Tomatoes were mechanically transplanted in a single-line per bed with a 30 cm within row plant spacing. The tomato cultivar was ‘HM 58841’, which is widely used in the region.

2024 Planting date study

In addition to the grafted cultivar study, a planting date study evaluating three planting dates was conducted in the same infested field. Transplanting dates were April 9, May 1, and June 10, 2024. These correspond to early, middle, and late planting dates for this region of the Sacramento Valley. The trial was arranged in a randomized complete block design with six replications of each planting date treatment. Individual plots were a 36 m long x 1.5 m bed. The first and second planting dates were mechanically transplanted with HM 58841 in a single plant line per bed and 30 cm plant spacing while the third planting date was planted with HM 8237 due to limited availability of HM 58841.

Data collection and statistical analysis

In all studies, plots were monitored weekly for broomrape emergence. Broomrape clusters were marked with wire construction flags, with different colors representing each week's emergence (Fig. 1). At commercial tomato maturity, trials were terminated and the number and color of flags in each plot were recorded. Data were analyzed using t-test or one-way analysis of variance followed by a Tukey-HSD in RStudio version 1.2.5033.

Results

Variations in resistance across cultivars

Greenhouse pilot study 2022

Broomrape emergence was first noted 56 days after transplant (Table 1). The last pot with emergence was noted on March 28, 2022, 102 days after planting at which point the experiment was terminated. The average number of days to emergence ranged from 71-93 DTE (Table 1). The cultivar with fastest average broomrape emergence was 'N 6434' with an average of 71 DTE, while 'HM 58841' had the slowest average emergence at 93.3 DTE (Table 1). However, there were no significant difference in days to emergence among cultivars evaluated in this study (P=0.56, Table 1).

2023 Greenhouse screening study

Broomrape emergence was first noted 64 days after transplant and the latest on June 13, 2023, 89 days after transplant. Average DTE and GDD to emergence were 68-87 DTE and 725-924 GDD, respectively (Table 1). There were differences in DTE and GDD among cultivars, wherein 'SVTM 9025' had significantly lower DTE and GDD than 'H9553' (P = 0.05); the remaining cultivars were not significantly different from these two cultivars or one another (Table 1). The cultivar 'SVTM 9024' from the original 2021 field study did not have significant variation in resistance among the other cultivars (Table 1). Of note, the cultivar with the longest DTE in this study (SVTM 9025) was not included in downstream field trials.

2024 Greenhouse screening study

There was no broomrape emergence in this study in any tomato cultivar or line. The study was planted in May 2024 in a non-quarantine greenhouse facility recently approved for branched broomrape research; however, this location had a less robust cooling system than the CRF greenhouse used in earlier studies. The trial was also planted in early summer rather than the winter or spring as in previous trials. It is likely that high outdoor temperatures and insufficient cooling inside of the greenhouse affected broomrape dormancy. Branched broomrape requires specific conditions for preconditioning to release seeds from dormancy, and even if they are initially met, the seeds can enter secondary dormancy if the soil conditions change before seeds are germinated (Murdoch and Kebreab, 2013). The temperatures inside of the greenhouse regularly exceeded the top range of the conditions required for preconditioning (5-30 C), which likely contributed to the lack of broomrape emergence during this experiment (Murdoch and Kebreab, 2013). Future experiments will be conducted during cooler periods of the year to replicate the failed 2024 trial.

Field studies

Among the six combinations planted in 2022, only one cultivar had broomrape emergence. The grafted combination of '1628' x 'CG4069' had broomrape emergence in all four replications. The non-grafted control cultivar, 'N6428', did not have broomrape emergence in any of the plots. Due to logistical constraints related to receiving the grafted transplant material, this trial was planted late for the region. The variability in results could be due to the late planting date, as seen in the 2021 chemical efficacy study mentioned in the introduction.

There was broomrape emergence in every plot of each cultivar planted in the 2023 field study but there were no significant differences among cultivars (Table 2). Broomrape emergence by cultivar was as follows: SVTM 9016 had 16 clusters on average, SVTM 9019 had 22 clusters on average, and HM 8237 had 13 clusters on average (Table 2). In the unreplicated demonstration study, the rows planted with HM 58841 had 8 and 9 clusters per 36 m plot, while the rows planted with H9553 had 4 and 12 clusters per plot (data not shown). While statistical inferences cannot be made from these observational data, there did not appear to be substantial differences in broomrape sensitivity between H9553 and HM 58841 (data not shown). In 2024, there was broomrape emergence in every plot of each combination planted (Table 2). There were no statistical differences in broomrape emergence among the grafted combinations.

Planting date studies

In the 2022 planting date study, the average number of broomrape clusters per plot in the early May planting was 52 per 30 m plot, while the late May planting was 52% lower (25 per plot) (Table 2). While not statistically significant due to within-treatment variability (P=0.21), these results were somewhat promising given the numerical differences. In the 2024 planting date study, there were significant differences in broomrape emergence among planting dates (P = < 0.001). The earliest planting date had an average of 90 broomrape clusters per 30 m plot, while the middle planting date was 91% lower, with an average of 8 per plot (Table 2). The late planting did not have any broomrape emergence; however, it must be noted that some of the plots planted at this time had poor stand due high temperatures and heavy weed pressure.

Discussion

Branched broomrape presents a major threat to the California tomato and specialty crop seed industries. Its regulatory status as a "A-listed" noxious weed necessitates strict quarantine procedures if found in a commercial field (Kelch 2017). Due to the nature of these regulatory procedures and lack of crop insurance, affected growers are faced with a massive economic loss if they report an infested field. Currently the economic threshold for branched broomrape is zero due to its regulatory status. Fumigation of infested fields can release quarantine fields from regulatory measures, but this is not financially viable for the majority of growers affected, with fumigation costs over $10,000 USD per hectare. In addition to high costs, the chance of reinfestation is very high in this highly-mechanized production system, with equipment from in-house and external farming operations moving in and out of fields throughout the season. Researchers at UC Davis are developing best management practices for equipment sanitation to mitigate the spread in and among fields in California (Hosseini et al. 2022). Although there are now products registered for in-season management, industry and researchers must seek additional measures for managing this pest in already infested fields and mitigating the spread to non-infested fields (Anonymous 2022). Successful sustainable long-term management of many plant pathogens can be achieved with resistant cultivars, and ultimately this should be the goal for processing tomatoes in California. Until then, additional measures such as the development of herbicide programs to manage existing populations, evaluation of various cultural control methods to bolster in-season chemical management tools, and the deployment of equipment sanitation practices to contain infestations and mitigate the spread of this pest.

Field and GH studies in which total emergence was evaluated suggested little difference among culitvars; however, there did appear to be some variation in timing of broomrape emergence within commercial cultivars evaluated in the GH. In 2022 and 2023 greenhouse studies, the cultivar planted in the 2021 field study with no broomrape emergence ('SVTM 9024') proved susceptible to broomrape parasitism and did not have significantly later emergence than other cultivars. Field studies did not include this cultivar or many other screened in the greenhouse studies due to logistical limitations. Future field studies could include additional commercial cultivars that were previously screened in greenhouse studies and collect temporal emergence data to confirm the results found in greenhouse studies under field conditions. While the current economic threshold remains zero, studies evaluating variation in resistance among commercial cultivars and the potential effect of this variation on yield would be extremely valuable to California tomato growers.

Breeding for durable resistance to broomrapes has targeted several pathways in the tomato plant. Dor et al. (2009) discovered that tomato mutant Sl-ORT1 was significantly more resistant to Egyptian broomrape parasitism than the control cultivar M-82 under greenhouse and field conditions. They determined through grafting experiments that resistance was conferred through the rootstock of grafted tomato plants, not the scion (Dor et al. 2009). However, the Sl-ORT1 mutant exhibited a significantly higher number of unsuppressed lateral stem branches versus control M-82 (Dor et al. 2009). Koltai et al. (2010) later determined that Sl-ORT1 produced lower amounts of two strigolactones. They determined that these strigolactones were involved in the regulation of lateral branching in tomatoes and other plant species and key factors in mycorrhizal colonization of host plant roots as a stress response (Koltai et al. 2010). Further research into SL mutants confirmed SLs role in suppression of lateral branching and as a result, severe yield loss seen in SL mutant lines (Karniel et al. 2024). Bai et al. (2020) screened 50 wild type tomato accessions for resistance to Egyptian broomrape. They found that three wild type accessions were promising for further study, with one accession, *S. pennellii* LA0716, exhibiting very high resistance to Egyptian broomrape (Bai et al. 2020). LA0716 was tested against M-82 in greenhouse settings, and had significantly lower attachment of broomrape radicles; the few radicles that attached to LA0716 became brown and later died due to apparent incompatibility (Bai et al. 2020). El-Halmouch et al. (2006) also studied LA0716 and suggested that its resistance is likely a result of low SL exudation and inhibition of tubercle development, findings that were corroborated by Bai et al. (2020). Bai et al. (2020) determined that callose deposition and root lignification contributed to inhibited tubercle development and broomrape resistance in LA0716. Durable resistance to broomrapes is complex and has been difficult to achieve in processing tomato.

Currently, there are no commercially available cultivars with qualitative broomrape resistance. It is currently possible to graft non-SL mutant scions onto SL-mutant rootstocks and is done at a limited scale. Grafting has historically been done by hand and was/is very expensive and difficult to scale for application in processing tomato production; however, with the development of automated grafting machines and commercially-available resistant rootstocks, this technique may become more feasible in coming years (Karniel et al. 2024). Long-term broomrape management will depend on durable qualitative resistance; however, this will likely take some time before being commercially available. Until then, variation in resistance among commercially cultivars should be leveraged along with delayed transplanting to reduce broomrape population in currently infested and at-risk fields. Variations in temporal emergence combined with delayed transplanting is a technique that can be implemented now to reduce the window of broomrape germination, attachment, emergence, and ultimately, seed set. Further research should be conducted in both the field and greenhouse to further validate and quantify variation in resistance as well as the effects of delayed transplanting. However, there are tomato processors that are beginning to implement later planting dates for fields that are at risk of infestation or have known infestations (ZB, personal communication). Future research should also work to validate the resistance of commercially-available broomrape-resistant rootstocks with grafted tomato cultivars under California conditions. With the development of high-throughput automated grafting technologies in California in combination with resistant rootstocks, growers and processors may be able to justify the higher costs of grafting plants by planting in infested or at-risk fields.

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Competing Interests

The authors declare none.

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Tables

Table 4.1. Average number of days after transplant to first branched broomrape emergence among 20 of the most widely planted processing tomato cultivars in California and several precommercial lines from two greenhouse studies conducted in 2022 and 2023.

Cultivar	2022 Greenhouse pilot study DTE	2023 Greenhouse study DTE		2023 Greenhouse study GDD	
n=	3	3		3	
N6428	82.3	76	ab	805	ab
HZ 1662	82	76	ab	805	ab
HM 58841	93.3	84	ab	892	ab
BP13	77	80	ab	849	ab
SVTM 9013	89.3	78	ab	832	ab
SVTM 9016	82.6	81	ab	860	ab
HM 5235	83.3	79	ab	835	ab
SVTM 9024	86.6	76	ab	809	ab
HMX 4909	79	83	ab	880	ab
H1015	75.6	81	ab	860	ab
SVTM 9025	92	68	b	725	b
SVTM9011	75	81	ab	860	ab
HZ 1428	83	81	ab	880	ab
N 6434	71	80	ab	849	ab
SVTM 9013	84.3	76	ab	806	ab
BQ403	79.6	73	ab	774	ab
HZ 5706	77.6	83	ab	880	ab
BQ413	76.3	75	ab	798	ab
DRI 0319	77	77	ab	860	ab
BQ 273	83	80	ab	849	ab
Syngenta	-	80	ab	849	ab
Seminis Dynafort	-	76	ab	805	ab
Seminis Multifort	-	87	a	924	a
H 5508	-	78	ab	829	ab
H 9553	-	87	a	924	a
p-value	0.56	0.05		0.05	

DTE: days to emergence. GDD= growing degree days. Cultivars that share the same letter are not significantly different from one another (p=0.05). In the 2022 and 2023 studies, all reps of every cultivar were parasitized by the time trials were terminated, at 102 and 89 days after planting, respectively. There was no emergence in the 2024 study.

Table 4.2. Branched broomrape emergence data from three field seasons of cultivar and planting date studies conducted near Woodland, CA.

Year	n	Variable	Broomrape Clusters/30 m	
Cultivar/line comparisons				
2022^	4	N6428	0	a
June 6		N6428 x 6575^^	0	a
		N6428 x Ground Force^^	0	a
		1628 x CG4069^^	1	b
		Balance rootstock ungrafted	0	a
		Ground Force rootstock ungrafted	0	a
p-value			< 0.001	
2023	8	SVTM 9016	16	
May 21		SVTM 9019	22	
		HM 8237	13	
p-value			0.23	
2024	5	H1996 x CG6094^^	62	
April 9		H1996 x CG4069^^	60	
		H1996 x CG6575^^	49	
p-value			0.74	
Planting date comparisons				
2022	4	May 3	52	
HM 58841		May 20	25	
p-value			0.21	
2024	5	April 9	90	a
HM 58841		May 1	8	b
		June 10	0	b
p-value			< 0.001	

Means within an experiment and year that share the same letter are not significantly different from one another.

^2022 cultivar study plots were 5 m; the plots in all other studies were 30 m

^^ scion and rootstock combination

Figures

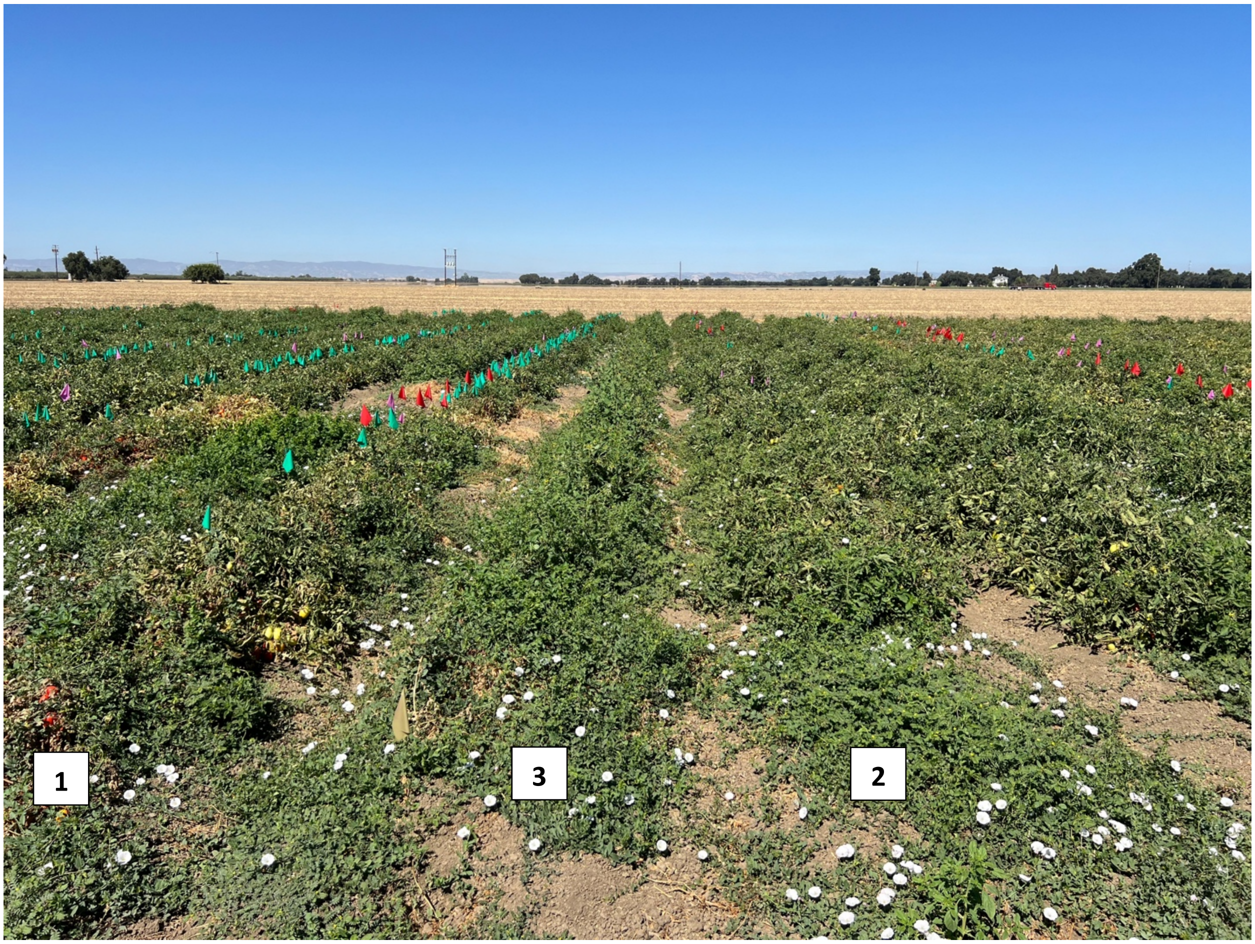

Figure 4.1 Tomatoes from a 2024 planting date study near Woodland, CA, with flags marking individual broomrape clusters in one replicate of the early (1), mid (2), and late (3) planting dates approximately 110 days after the first transplant date.