Title
Evaluating branched broomrape (Phelipanche ramosa) management strategies in California processing tomato (Solanum lycopersicum)

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Evaluating branched broomrape (*Phelipanche ramosa)* management strategies in California processing tomato (*Solanum lycopersicum*)

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Abstract

Recent detections of branched broomrape (*Phelipanche ramosa*) in California tomato (*Solanum lycopersicum*) fields have led to increased interest in herbicide treatment programs to control this regulated noxious weed. Broomrapes (*Phelipanche spp.* and *Orobanche spp.)* are parasitic weeds that pose a significant risk to the processing tomato industry for several reasons that include California's Mediterranean climate which is similar to that of branched broomrape's native range, California agronomic practices (wide variety of host species cultivated, successive tomato crops, shared equipment) make the proliferation and spread of broomrape in and among fields highly likely, and broomrape's phenological development makes it difficult to monitor and inaccessible to conventional weed control practices. In addition, California's regulatory environment make soil fumigation difficult and costly and herbicides unavailable, while branched broomrape's regulatory status as quarantine pest does not incentivize accurate reporting.

A decision support system and herbicide treatment program, known as PICKIT, was developed over two decades of research in Israel, and has been proven to provide successful management of Egyptian broomrape (*P. aegyptiaca*) in tomato. The PICKIT system uses a thermal time model to forecast the belowground development of the parasite in order to precisely time the application of ALS inhibitor herbicides to target specific broomrape life stages. Research was conducted in 2019 and 2020 to determine if the PICKIT system could be adapted to manage branched broomrape in California processing tomatoes and to provide herbicide registration support data.

Treatment programs based on the PICKIT system herbicides sulfosulfuron and imazapic were evaluated in 2019 and 2020 for crop safety on processing tomato. Treatments included

several combinations of preplant incorporated (PPI) sulfosulfuron applications paired with different rates of imazapic either injected into the drip system (chemigation) or applied as foliar treatments. There were no significant differences in phytotoxicity or tomato yield among herbicide treatments in the three experiments. Additionally, a rotational crop study was conducted in which a tomato crop received PICKIT treatments in 2019 and several common rotational crops were planted and evaluated in 2020. Corn planted after the sulfosulfuron treatment suffered chlorosis and stunting, however, safflower, sunflower, melons, and beans were not injured by any of the treatments. After two field seasons, the PICKIT decision support system seems to have reasonable crop safety on processing tomato under California conditions. Rotational crop restrictions will need to be considered if branched broomrape becomes widespread in California and sulfosulfuron becomes part of a broomrape management program.

An efficacy study was conducted in 2020 to evaluate the efficacy of a modified PICKIT system in California growing conditions. The study took place in an commercial field near Woodland, CA, reported to be infested with branched broomrape in 2019. This trial examined the efficacy of the PICKIT herbicides sulfosulfuron and imazapic as well as imazapyr, imazethapyr, and imazamox for control of branched broomrape.

There were 12 treatments replicated four times, and 47 out of 48 plots (45 m^2) had broomrape emergence. On average, non-PICKIT treatments had 38 broomrape clusters per plot while PICKIT treatments had 13 clusters per plot. There was a trend in which the PICKIT treatments had fewer broomrape shoots per plot than the non-PICKIT treatments, however, there were no significant differences in the number of broomrape shoots among PICKIT treatments. None of the treatments eliminated broomrape emergence; more studies evaluating PICKIT treatments should be conducted to improve the efficacy of individual treatments. Branched broomrape and Egyptian broomrape differ in phenological development and future research will investigate alternate chemigation times based on this difference. Futhermore, future research will evaluate and focus on imazamox, another imidazolinone herbicide, as this product is already registered in California on alfalfa and has a more promising registration pathway than imazapic.

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Introduction

Processing tomatoes are an important cash crop to annual agricultural systems in the Central Valley of California. California processing tomatoes have an annual farm gate value of \$1.17 billion and are currently the 10th most valuable agricultural commodity produced in the state (Winans, 2019; CDFA, 2020). In 2020, California produced 11.4 million tons of tomatoes across 230,000 acres, making up over 95% of US tomato production (USDA, 2020). California is also important on the international market, producing about 30% of the world's processing tomatoes (Winans, 2019).

The San Joaquin and Sacramento Valleys are the two major tomato growing regions in California, with five counties comprising the majority of the production acreage (Fresno, Yolo, Merced, King, and San Joaquin) (NASS, 2021). The California tomato industry is based on grower-processor contracts in which variety, amount, and often management are agreed upon before planting. Tomatoes typically are transplanted from March until July and harvested from July until October. Tomatoes are mostly planted in single or double plant lines on 60-inch, 66-inch, or 80-inch beds. The industry has widely adopted drip irrigation technology in recent decades, replacing furrow flood irrigation. Tomatoes are mechanically harvested when about 90% of the fruit are red and transported directly to processing facilities. With advances in genetics, management, and equipment, California processing tomato fields produce 50 tons of fruit per acre on average (USDA, 2020). The California tomato industry is highly specialized and utilizes many aspects of 'custom farming' in which a sub-contractor provides a specific service to the grower or processor. Tomatoes are mechanically transplanted, often by a third-party transplanting company or processor that may serve multiple growers and whose equipment may be used in many different fields each season. Tomato harvest follows a similar scheme, with harvesting companies or processors owning and operating harvest equipment, harvesting many fields across the state each year.

California tomato growers must manage a variety of pests, including several weed species. Major weeds include black nightshade and hairy night shade (*Solanum nigrum, Solanum physalifolium*), field bindweed (*Convolvulus arvensis*), and small seeded broadleaves (Miyao et al., 2021). Conventionally grown tomatoes utilize a combination of pre-emergence and post-emergence herbicides along with cultivation and hand weeding for effective weed control. Before planting, a preplant incorporated (PPI) herbicide is usually applied to the bed surface and incorporated with tillage equipment during final bed shaping. Common PPI or pre-emergence herbicides used in tomato include trifluralin (Treflan), rimsulfuron (Matrix), pendimethalin (Prowl H2O), S-metolochlor (Dual Magnum), and metribuzin (Metribuzin 75) (Miyao et al., 2021). Later in the season, common post-emergence herbicides include clethodim (SelectMax), halosulfuron (Sandea), metribuzin, rimsulfuron, sethoxydim (Poast), and carfentrazone (Shark EW) (Miyaoet al., 2021). Integrated weed management control practices include crop rotation, use of transplants, drip irrigation, and cultivation (Miyao et al., 2021).

Broomrapes belong to the *Orobanche* and *Phelipanche* genera in the Orobanchaeceae family (Bennet and Matthews, 2006). Broomrapes are obligate parasites, lacking chlorophyll, thus gaining all of their nutrients from parasitized host plants (Westwood, 2013). Of the numerous broomrape species, seven are economically important to agricultural crops globally (Eizenberg and Goldwasser, 2018). These include crenate broomrape *(Orobanche crenata),* nodding broomrape *(Orobanche cernua),* sunflower broomrape *(Orobanche cumana),* foetid broomrape *(Orobanche foetida),* small broomrape *(Orobanche minor),* Egyptian broomrape *(Phelipanche aegyptiaca),* and branched broomrape *(Phelipanche ramosa)* (Parker, 2009). These broomrapes parasitize plants from the Apiaceae, Asteraceae, Brassicaceae, Fabaceae, and Solanaceae families including crops such as carrot, sunflower, rapeseed, faba bean, and tomato (Parker and Riches, 1993). Broomrapes cause economic damage to agricultural crops by reducing yield, with reproductive tissue disproportionately affected (Fernandez-Aparicio et al, 2016). In Chile, tomato growers report up to 80% crop loss in fields infested with branched broomrape (Kogan, 1994), while growers in Sudan have reported total crop failure (Hershenhorn et al., 2009). Yield losses from broomrape infestations are thought to amount to $200 million annually in Turkey (Hershenhorn et al., 2009). Broomrape population density has increased in many near eastern and north African countries (Algeria, Egypt, Ethiopia, Morocco, Tunisia, Sudan, and Syria) alongside production of broomrape-sensitive crops, threatening food supply in this region (Abang et al., 2007). Parasitic plants, including broomrapes, threaten the food security of communities around the globe, and research must be conducted to develop management strategies to reduce yield and economic losses (Goldwasser and Kleinfield, 2004).

Branched broomrape (*Phelipanche ramosa* syn. *Orobanche ramosa*) is a parasitic plant native to the Mediterranean region of Eurasia. It is a holoparasite that parasitizes a host plant's root system resulting in loss of vigor, yield reduction, and even death to the host (Fernandez-Aparicio et al., 2016). In the United States, there are four species of weedy broomrapes known to parasitize economically important agricultural crops: small broomrape, Louisiana broomrape (*Orobanche ludoviciana),* Egyptian broomrape, and branched broomrape (Jain and Foy, 1989). In the past several years, branched broomrape and Egyptian broomrape have been reported in California, including Yolo, Solano, and San Joaquin counties (Miyao, 2016). In California, branched broomrape is "A" classified, being "an organism of known economic importance subject to California State enforced action involving eradication, quarantine regulation, containment, rejection, or other holding action," while Egyptian broomrape is classified as a "Q-listed" noxious weed (having "A-listed" classification pending permanent state determination) (Kelch, 2017). A field reported to be infested with an "A-listed" pest such as branched broomrape will be evaluated by the local county agriculture commissioner, quarantined, and that season's crop destructed. For at least two years following this discovery, a hold order is placed on the field and only approved non-host rotational crops may be planted. Broomrape has been discovered in conventional, intensely managed fields, suggesting that conventional weed control practices and currently registered herbicides do not provide adequate broomrape control. Currently there are no proven management practices to selectively control branched broomrape in tomato, making this parasitic weed a serious threat to the California processing tomato industry.

Branched broomrape was first discovered in California in 1903 in Butte County, followed by discoveries in Alameda, Colusa, Sacramento, San Benito, Santa Clara, San Joaquin, Ventura, and Yolo Counties (Hrusa, 2008; Osipitan et al., 2021). After a severe infestation was discovered in the Sacramento Valley in 1959, an intense industry wide eradication effort began at a cost of $1.5 million funded by a marketing order program (CTRI, 2019). From 1973-1982, field scouting combined with fumigation with methyl bromide reduced broomrape seed banks and eradication was thought to have been successful (CTRI, 2019).

Branched broomrape is considered to be one of the most common and destructive broomrape species, infesting 2.6 million hectares of crops across Asia, North Africa, and the Mediterranean (Mauromicale et al., 2008). Branched broomrape's reemergence in California is extremely concerning to the viability of the California processing tomato industry for several reasons. California's Mediterranean climate is similar to branched broomrape's native range, agronomic practices (wide variety of host species cultivated, successive tomato crops, shared equipment) make the proliferation and spread of broomrape's minute seeds in and among fields highly likely, while broomrape's phenological development make it inaccessible to conventional weed control practices and infestations difficult to detect. California's regulatory environment make soil disinfetation via fumigation difficult and costly and there are no registered herbicides for broomrape control.

Broomrape control strategies should focus on preattachment or very early during their lifecycles, when they are most vulnerable and before yield loss occurs (Fernández-Aparicio, 2016). Broomrape's unique phenology, specifically how it develops below the soil surface for 2/3 of its lifecycle, makes it unavailable to many conventional weed management techniques such as cultivation, post emergent herbicides, hand rogueing, etc. In addition, rapid progression from emergence to flowering and relatively small stature make scouting for the parasite in tomato fields extremely difficult.

Broomrape seeds are extremely small (0.2-0.4 mm). Their small size results in limited seed carbohydrate reserve and broomrape species have evolved mechanisms to ensure successful host attachment. Broomrapes require several specific conditions for germination: a stratification period, sufficient soil moisture, and detection of specific root exudates (Eizenberg and Goldwasser, 2018; Fernández-Aparicio et al., 2016). The stratification phase prepares seed receptors for detection of host root exudates (Musselman, 1980). Broomrape respond to a group of hormones known as strigolactones which include orobanchol, didehydroorobanchol, and solanacol (Fernández-Aparicio et al., 2011, 2016; Yoneyama et al., 2013). The detection of these exudates ensures the seed is within an acceptable distance to a host plant so that the broomrape radicle can intercept a host root and begin to form a haustorium. A haustorium is a modified root structure that connects parasitic plants to the host plant's root vascular system, allowing the broomrape to become a sink for water and nutrients (Eizenberg and Goldwasser, 2018). After sufficient nutrients have accumulated, the broomrape will form a swollen nodule known as a tubercle to store nutrients and water (Eizenberg and Goldwasser, 2018). As the parasite matures, shoots will form from this tubercle, emerge above the soil surface, develop flowers that self-pollinate, and produce seed.

Egyptian broomrape is the most limiting factor in tomato production in Israel and many neighboring countries accounting for 30% of total losses caused by all agronomic constraints and resulting in annual losses of up to $5 million (Hershenhorn et al., 2009). In Ethiopia, as of 2009, state sponsored farms had given up growing processing tomatoes in historically fertile regions because of broomrape infestations (Hershenhorn et al., 2009). In northern Israel, increasing infestations of broomrape over the last 30 years caused many growers to abandon tomato in lieu of less profitable non-host crops (Hershenhorn et al., 2009). Chile has historically faced challenges with broomrape in processing tomatoes (Kogan, 1994), and the parasite has become increasingly widespread in that country.

Researchers in Israel have developed a decision support system, named PICKIT, to manage Egyptian broomrape in processing tomatoes (Eizenberg and Goldwasser, 2018). The PICKIT system relies on a growing degree day (GDD) based model to inform precise applications of targeted chemical applications. The PICKIT system has various herbicide programs related to different infestation levels and relies on pre-plant incorporated treatments (PPI), chemigation treatments (CHEM), and foliar treatments. The PICKIT system utilizes two acetolactate synthase (ALS) herbicides to control broomrape; a sulfonylurea applied preplant in conjuction with low dose applications of an imidazolinone. These herbicides include sulfosulfuron (PPI) and imazapic (CHEM). These applications are made according to the GDD model to target specific broomrape development stages, specifically when it is a nutrient sink on the tomato plant, resulting in rapid translocation of herbicide from the host to the parasite. In 2016, commercial tomato growers in Israel deployed the PICKIT system and achieved 95% Egyptian broomrape control in 33 fields (Eizenberg and Goldwasser, 2018). Israeli researchers have partnered with Chilean researchers to adapt the PICKIT system to Chilean processing tomato growing conditions. Chile, like California, has infestations of branched broomrape (Galaz, J.C., personal communication, July 27, 2020)

Branched broomrape has been found in several counties in California, including two of the top five producing counties (Yolo and San Joaquin). While currently an "A-list" quarantine pest requiring crop destruction, there is a high likelihood this pest will become widespread enough to require management programs like any other weed. The PICKIT system developed in Israel could provide similar management in California. However, because there are differences between the Israeli and California processing tomato systems (climate, irrigation, soil type, crop rotations, variety, etc.) and broomrape species (branched vs. Egyptian), the PICKIT program must be evaluated and calibrated for use in California cropping systems. Imazapic is registered in the southern United States for use as an early post-emergence herbicide in peanuts but is not registered in California for use on any crops. Sulfosulfuron is registered in many states for use as a selective systemic herbicide on broadleaf weeds in wheat and is registered in California for non-crop use but not in tomato (Anonymous, 2011; and 2016). In order for these herbicides to potentially be registered under an emergency use authorization for broomrape control or an indemnified label under California production conditions, there must be research on their performance and crop safety. The overall goal of this study was to determine if there was potential to adapt the PICKIT decision support system for branched broomrape control in California processing tomatoes and to provide herbicide registration support data needed to register PICKIT herbicides for special use in California. To evaluate the PICKIT system under California conditions, a series of crop safety and efficacy field experiments were conducted in 2019 and 2020.

Materials and Methods

Crop Safety Evaluations

Three crop safety studies and two supplemental dose-response evaluations were conducted in 2019 and 2020 to evaluate the crop safety of the Israeli-developed PICKIT decision support system (DSS) on California processing tomatoes. These studies were conducted at the UC Davis Plant Sciences Field Research Facility near Davis, California (38.539105, 121.783547). The soil composition at this site was 41% sand, 34% silt, and 25% clay with 2.1% OM, 6.98 pH, and estimated CEC of 18.2 $cmol_c$/kg of soil. The site did not contain broomrape; this protocol focused on crop safety of 1X and 2X rates of herbicides used in the PICKIT system that are not currently registered for use in tomato in the United States. Plots were 12 m long on 1.5 m beds with one plant line in the center of the bed. Cultivar 'Heinz 1662' processing tomato transplants were planted at 30.5 cm spacing. Each bed had two 15.9 mm drip lines buried at 30.5 cm with 0.6 L/hr emitters spaced every 30.5 cm; one line ran the full length of the beds and was used for crop irrigation and fertigation, the second line was terminated at the end of each plot and connected to an above-ground manifold system which was used to apply the experimental chemigation herbicide treatments. Plots were arranged in a randomized complete block design with four replications per treatment. In 2019, two experiments were conducted to represent two planting dates, April 25 and May 30; a single experiment was conducted in 2020 with an April 22 planting date.

Pre-plant incorporated (PPI) applications of sulfosulfuron were made one day before transplanting on April 24 and May 29, 2019 in the early- and late-planted experiments respectively, and on the day of planting, April 22, 2020 (Table 1). PPI herbicides were applied using a backpack sprayer and three-nozzle boom delivering 280.5 L/ha (30 gallons per acre, GPA) with AIXR 11003 nozzles at 28 pounds per square inch (PSI). PPI treatments were mechanically incorporated to 7.6 cm after application, after which tomatoes were mechanically transplanted with a three-row transplanter on April 25, 2019 (early planting), May 30, 2019 (late planting), and April 22, 2020.

The PICKIT system's thermal time model is based on growing degree days (GDD), with applications at 400, 500, 600, 700, and 800 GDD after transplanting depending on treatment regimes (Table 1). The PICKIT program has various regimes depending on level of infestation, with each calling for different application types (PPI, chemigation, foliar) and total number of applications (Table 2). In 2019, chemigation applications were made through the terminated irrigation line using a 20.8 L/min 12-volt electric pump and 113.5 L tank. Treatments were applied to four plots at once, with a total carrier volume of 96.1 L per treatment resulting in approximately 15.9 L per plot (18.3 m^2). In 2020, chemigation applications were made using CO_2 to inject a chemigation mix into a distribution manifold with valved connections at each plot (Figs. 1, 2). Treatments were applied to two replicate plots at once with separate injection ports for replicates 1 and 2 and replicates 3 and 4 to reduce the system volume receiving herbicide-treated water. Herbicides were diluted in 11 L of water and this solution was injected into the already-running irrigation system over approximately 15 minutes, followed by 20 minutes of water to flush the distribution lines. Foliar imazapic treatments were made on July 16, 2019, August 15, 2019, and June 12, 2020 and approximately 21 days later (August 6, 2019, September 6, 2019, and July 6, 2020) with a backpack sprayer and two-nozzle boom delivering 280.5 L/ha (30 GPA) with AIXR 11005 nozzles at 20 PSI. These applications were made at estimated broomrape emergence and approximately 21 days later, as these studies occurred in uninfested fields. Phytotoxicity (percent affected plants) was recorded in all three studies and representative plant height (cm) was recorded in the 2020 study. All fruit from one-meter square sections of row were harvested on September 4, 2019, September 19, 2019, and September 3, 2020 at commercial maturity and fresh weights were recorded (Fig. 3, Tables 6, 7). Phytotoxicity, height, and yield data were analyzed using a one-way analysis of variance followed by a Tukey-HSD test using the *agricolae* package in R version 1.2.5033 (De Mendiburu, 2021; Kniss and Streibig, 2018).

Two supplemental crop safety trials were conducted to evaluate increasing rates of foliar applied imazapic, which is not currently registered on processing tomatoes in California. These studies were conducted at the UC Davis Plant Sciences Field Facility near Davis, CA, (38.539105, 121.783547). Cultivar ‘Heinz 1662’ tomatoes were transplanted on April 22, 2020 in a single plant line on a 1.5 m bed with 30.5 cm spacing. Imazapic was applied late in the growing season to simulate a rescue application in a PICKIT program. Applications were made on July 7, 2020, 73 days after transplant in the first experiment and on July 21, 2020, 87 days after transplant in the second experiment at 280.5 L/ha (30 GPA) using a two-nozzle boom with AIXR 11003 nozzles at 28 PSI. Five rates were applied in a dose response style experiment (Table 9) with a 0.25% v/v nonionic surfactant (Rainier). Applications were made at full fruit set (100% green fruit). Each treatment was replicated four times in a single guard row of an existing processing tomato experiment. Visual crop injury ratings were taken 3, 7, and 14 days after treatment (DAT). Phytotoxicity means were analyzed using a one-way analysis of variance followed by a Tukey-HSD test using the *agricolae* package in R version 1.2.5033 (De Mendiburu, 2021; Kniss and Streibig, 2018).

Table 1. Growing Degree Day targets and actual application dates of PICKIT tomato crop safety experiments near Davis, CA.

Growing Degree Day Target	**2019 Early Planting**	**2019 Late Planting**	**2020 Planting**
Preplant Incorporated (PPI)	24-April	29-May	2-April
Transplant	25-April	30-May	22-April
400	5-June	13-June	13-May
500	7-June	20-June	21-May
600	11-June	24-June	27-May
700	13-June	28-June	1-June
800	20-June	3-July	3-June
Foliar (at est. BR emergence)	16-July	15-August	12-June
Foliar (approx. 21 days after est. BR emergence)	6-August	6-September	6-July

BR= broomrape

Cumulative Growing Degree Days (GDD) were calculated after planting date by using the formula $GDD = \sum(\bar{T} - T_b)$, where $\bar{T}$ is mean daily temperature and T_b is the base temperature set at 10 °C (50 degrees Fahrenheit).

Table 2. 2019 and 2020 PICKIT tomato crop safety treatment list.

Trt	**Treatment**	**Application**	**Rate g ai/ha**	**Application timing**
1	Control	na	na	na
2	Control 2^	na	na	na
3	Sulfosulfuron	PPI	37.5	Before transplant
	Imazapic	CHEM x5	4.8	400, 500, 600, 700, 800 GDD
4	Sulfosulfuron	PPI	37.5	Before transplant
	Imazapic	CHEM x2	4.8	400, 600 GDD
5	Imazapic	POST x2	2.4	BR emergence and approx. 21 days later
6	Sulfosulfuron	PPI	70	Before transplant
	Imazapic	CHEM x5	9.6	400, 500, 600, 700, 800 GDD
7	Sulfosulfuron	PPI	70	Before transplant
	Imazapic	CHEM x2	9.6	400, 600 GDD
8	Imazapic	POST x2	4.8	BR emergence and approx. 21 days later

BR= brooomrape, GDD= growing degree days, PPI= preplant incorporated
^Treatment 2 was a placeholder for a commercial standard PRE tank mix that was not applied in any of the experiments; instead, the entire field was treated with 350 g ai/ha S-metolachlor (Dual Magnum) and 91.9 g ai/ha trifluralin (Treflan).

Rotational Crop Safety Evaluations

A two-year study was conducted from spring 2019 to fall 2020 to evaluate rotational crop-safety of the Israeli-developed PICKIT decision support system. This field experiment included a 2019 tomato crop treated with PICKIT herbicides followed by a planting of six common rotational crops (wheat, corn, safflower, sunflower, beans, melon) in 2020. The study was conducted at the UC Davis Department of Plant Sciences Field Research Facility near Davis, California (38.539105, 121.783547).

The site did not contain broomrape; this experiment focused on crop safety (0.5X, 1X, 2X rates) of sulfosulfuron, imazapic, and 2X rates of imazamox, imazapyr, and imazethapyr, none of which are currently registered for use in tomato in the United States. The 2019 tomato main plots were 54.8 m long on 1.5 m beds with one plant line in the center of the bed. Each bed had one 15.9 mm drip line at a depth of 30.5 cm with 0.6 L/hr emitters spaced every 30.5 cm. This drip line was used for crop irrigation and fertigation as well as chemigation of PICKIT treatments. For the 2019 tomato crop, main plots were arranged as whole rows in a randomized complete block design with four replications.

PPI applications of sulfosulfuron were made on May 29, 2019 one day before transplanting tomatoes. PPI herbicides were applied using a backpack sprayer and three-nozzle boom delivering 280.5 L/ha (30 GPA) with AIXR 11003 nozzles at 28 PSI. PPI treatments were mechanically incorporated to 7.6 cm after application. Tomato cultivar 'DRI 319' transplants were planted at a 30.5 cm spacing with a three-row transplanter on May 30, 2019. At each growing degree day target chemigation applications were made through the drip line using a Venturi-style injection system attached to a cone tank over the course of 45 minutes, with treatments applied to four replicate plots at once (Table 3). A single one-meter square section of each plot was harvested on September 19, 2019 and total weight of all fruit were recorded (Table 10).

Following the tomato harvest in 2019, the tomato crop was destroyed in place with a flail mower. After the crop residue dried, beds were lightly cultivated to reshape beds but minimize soil mixing. The 54.9 m long tomato main plots were split into six 9.1 m subplots for the 2020 rotational crops in a split plot design. The six rotational crops including wheat, corn, safflower, sunflower, beans and melons were randomly assigned to a subplot such that the 2020 experimental design was a randomized split plot with four replications. On November 22, 2019, wheat subplots were planted with a grain drill. Visual wheat injury measurements were recorded during the winter of 2019 and spring of 2020. In mid-April 2020, all beds were treated with glyphosate to terminate the wheat and control winter weeds in all plots and lightly cultivated to prepare a seedbed. On April 17, 2020, corn (LG Seeds ES7514), safflower (CW99-OL), sunflower (S.O.C. France, 19044), beans (red kidney), and melons (Osborne 'Hale's Best Jumbo') were planted using an Earthway precision garden seeder (Earthway Products, Inc., Bristol, IN) (Fig. 5). Summer crops were irrigated with a single drip irrigation line on the soil surface. Plant height and fresh weight biomass (per 1 m of row) were recorded nine weeks after planting on June 23, 2020; the experiment was subsequently terminated without being taken to maturity. Height and fresh biomass data were analyzed using a one-way analysis of variance followed by a Tukey-HSD test with the *agricolae* package in R version 1.2.5033 (De Mendiburu, 2021; Kniss and Streibig, 2018).

Table 3. 2019 and 2020 Herbicide treatments applied to a tomato crop in a rotational crop safety study near Davis, CA.

Trt	Treatment Name	Application	Rate g ai/ha	GDD Application
1	Control	na	na	na
2	Sulfosulfuron 0.5X	PPI	18.75	na
3	Sulfosulfuron 1X	PPI	37.5	na
4	Sulfosulfuron 2X	PPI	70	na
5	Imazapic 1X	CHEM x5	4.8	400, 500, 600, 700, 800
6	Imazapic 2X	CHEM x5	9.6	400, 500, 600, 700, 800
7	Imazamox 2X	CHEM x5	9.6	400, 500, 600, 700, 800
8	Imazapyr 2X	CHEM x5	9.6	400, 500, 600, 700, 800
9	Imazethapyr 2X	CHEM x5	9.6	400, 500, 600, 700, 800

Application dates in 2019: PPI (5/29), 400 (6/1), 500 (6/25), 600 (7/1), 700 (7/5), 800 (7/15). Cumulative Growing Degree Days (GDD) were calculated after planting date by using the formula $GDD = \sum(\bar{T} - T_b)$, where $\bar{T}$ is mean daily temperature and T_b is the base temperature set at 10 °C (50 degrees Fahrenheit).

PICKIT Efficacy Evaluation

A study was conducted in a commercial tomato field in Yolo County, CA, that had been reported as infested with branched broomrape in 2019 and a portion of the crop was destroyed under CDFA quarantine provisions. The infested area was prepared for planting by the grower and used for a 2020 experiment to test the efficacy of the PICKIT protocol on branched broomrape in California tomato systems. The soil composition at this site was 25% sand, 42% silt, and 33% clay with 2.7% OM, 7.2 pH, and estimated CEC of 23.6 ($cmol_c$/kg of soil).

Plots were 30.5 m long on 1.5 m beds with two drip lines: one 22.2 mm drip line buried at 25.4 cm and one 25.4 mm drip line buried at 30.5 cm in the center of the bed. The 22.2 mm drip line was terminated at the ends of each plot serving as the dedicated chemigation line with 0.6 L/hr emitters at 30.5 cm spacing. The 25.4 mm line was used for crop irrigation and fertigation of the entire experimental area. Plots were arranged in a randomized complete block design with four replications.

PPI applications of sulfosulfuron were made on March 27, 2020 (Table 5). Sulfosulfuron was applied using a backpack sprayer and three-nozzle boom delivering 280.5 L/ha (30 GPA) with AIXR 11003 nozzles at 28 PSI. PPI treatments were mechanically incorporated to 7.6 cm after application on the same day. In addition to the experimental treatments, the entire plot area was treated with the grower's preplant incorporated tank mix, which consisted of S-metolachlor (350 g ai/ha), pendimethalin (87.3 g ai/ha), metribuzin (91.9 g ai/ha), and diazinon (734.9 g ai/ha) on March 27, 2020. Cultivar 'BQ271'were mechanically transplanted using a two-row transplanter on March 30, 2020 with two plant lines in each row with plants spaced 30.5 cm apart within and between lines. A routine foliar application of 7.2 g ai/ha rimsulfuron was made by the grower to the entire experimental area after transplanting.

Chemigation applications were made using CO_2 to inject the chemigation mix into 50.8 mm lay flat hose connected to valved 22.2 mm chemigation lines in each plot (Figs. 1, 2). Treatments were applied to two replicate plots at once; plots of the same treatment in replications 1 and 2 and replications 3 and 4 were treated together. Herbicide treatments were mixed in 11 L of solution which was injected into the already-running irrigation system over approximately 15 minutes, followed by 20 minutes of water to flush the lines. Chemigation applications were made according to a modified version of the PICKIT protocol (Tables 4, 5). Foliar imazapic treatments were made with a 2-nozzle backpack sprayer delivering 280.5 L/ha (30 GPA) with AIXR 11003 nozzles at 28 PSI.

Broomrape scouting was done 3 times weekly for seven weeks, followed by 1 time per week for 3 weeks starting on June 1, 2020. At each rating, individual clusters of shoots were marked with wire construction flags, with different colors representing each week's emergence (Figs. 5, 6). Broomrape shoot clusters were counted and recorded weekly. Total broomrape cluster numbers were analyzed using a one-way analysis of variance followed by a Tukey-HSD test in the *agricolae* package in R (De Mendiburu, 2021; Kniss and Streibig, 2018). Broomrape emergence over time was analyzed with a 3-parameter log-logistic function in the *drc* package in R version 1.2.5033 (Ritz et al. 2015; Kniss and Streibig, 2018).

Before the trial was terminated and after the final broomrape cluster count, locations of individual clusters marked by flags were recorded with a GPS device (Fig. 7). A Trimble Handheld GPS device was placed at each flag, the coordinate was recorded in the FarmWorksMobile application (Trimble, Sunnyvale, CA), and the color of the corresponding flag was recorded. This data was entered into ArcGIS online (ArcGIS.com), and a color-coordinated map was created (Fig. 8).

Table 4. Growing Degree Day targets and actual application dates in a 2020 PICKIT efficacy evaluation study on tomatoes near Woodland, CA.

Growing Degree Day Target	**Actual Application Date (2020)**
PPI	27-March
400	2-May
500	8-May
600	14-May
700	22-May
800	26-May
Imazapic POST at BR emergence	12-June
Rimsulfuron (Trt L)	12-June
Imazapic 21 days after BR emergence	25-June*

BR= broomrape

* This did not coincide with the recommended application timing of broomrape emergence and 21 days after; instead, the first application was made one week after broomrape emergence and the second application was 13 days after that.

Table 5. PICKIT treatments in a 2020 processing tomato field experiment near Woodland, CA.

Trt.	**Treatment**	**Application**	**Rate g ai/ha**	**GDD**
A	Control	na	na	na
B	Control 2^	na	na	na
C	Sulfosulfuron	PPI	37.5	na
	Imazapic	CHEM x5	4.8	400, 500, 600, 700, 800
D	Sulfosulfuron	PPI	37.5	na
	Imazapic	CHEM x2	4.8	400, 600
E	Imazapic	POSTx2	2.4	BR emergence, 21 days later
F	Sulfosulfuron	PPI	37.5	na
	Imazapic	CHEM x5	9.6	400, 500, 600, 700, 800
G	Sulfosulfuron	PPI	70	na
	Imazapic	CHEM x2	9.6	400, 600
H	Imazapic	POSTx2	4.8	BR emergence, 21 days later
I	Sulfosulfuron	PPI	37.5	na
	Imazamox	CHEM x5	4.8	400, 500, 600, 700, 800
J	Sulfosulfuron	PPI	37.5	na
	Imazapyr	CHEM x5	4.8	400, 500, 600, 700, 800
K	Sulfosulfuron	PPI	37.5	na
	Imazethapyr	CHEM x5	4.8	400, 500, 600, 700, 800
L	Rimsulfuron	POST	7.2	na

PPI= preplant incorporated POST= post emergence CHEM= Chemigated. BR= broomrape
Cumulative Growing Degree Days (GDD) were calculated after tomato transplanting date by using the formula $GDD = \sum(\bar{T} - T_b)$, where $\bar{T}$ is mean daily temperature and T_b is the base temperature set at 10 °C (50 degrees Fahrenheit).
^Treatment B was a placeholder for a commercial standard PRE tank mix that was not applied in any of the experiments; instead, the entire experimental area was treated with the grower's preplant incorporated herbicide program of S-metolachlor (350 g ai/ha), pendimethalin (87.3 g ai/ha), metribuzin (91.9 g ai/ha), and diazinon (734.9 g ai/ha) and also with a post-transplant application of 7.2 g ai/ha rimsulfuron.

Results

Crop Safety Evaluations

In the two 2019 PICKIT crop safety experiments, there were no differences in phytotoxicity on processing tomato among treatments (Tables 6, 7). Some phytotoxicity was recorded in the border rows of the early planting experiment but was likely a result of glyphosate drift from a neighboring fallow field rather than a chemigation treatment-related effect; extremely injured or dead plants were replaced with new transplants and the moderately injured plants grew out of initial injury. Tomato yield ranged from 16-24 kg per square meter in experiment 1 and 18-24 kg m^{-2} in experiment 2 (Tables 6, 7). There were no significant differences in tomato yield among treatments in either experiment ($p= 0.56, 0.69$). In the 2020 PICKIT crop safety experiment, there was no phytotoxicity or height reduction observed on processing tomato in any of the treatment plots (Table 8). Plant heights ranged from 52 to 56 cm and tomato fruit yield ranged from 17 to 21 kg m^{-2} row and there were no differences among treatments ($p=0.65$) (Table 8). There was no detectable crop injury at any rate in either imazapic dose response experiment with foliar imazapic applied at rates up to 72 g ai/ha (Table 9).

Table 6. Phytotoxicity and yield from PICKIT tomato crop safety experiment 1, transplanted on April 24, 2019, near Davis, CA

				Percent Phytotoxicity							**Yield kg/m^2 row**
Trt.	**Treatment**	**Rate g ai/ha**	**GDD Appl.**	**5/21**	**6/6**	**6/20**	**7/3**	**7/17**	**7/31**	**7/14**	**8/4**
1	Control	na	na	35.0	13.4	3.5	0.0	0.0	0.0	0.0	20.2
2	Control 2^	na	na	25.0	5.1	0.8	0.0	0.0	0.0	0.0	24.3
3	Sulfosulfuron	37.5	na	22.5	4.2	0.0	0.0	0.0	0.0	0.0	
	Imazapic	4.8	400, 500, 600, 700, 800								21.1
4	Sulfosulfuron	37.5	na	52.5	19.3	7.5	0.0	0.0	0.0	0.0	
	Imazapic	4.8	400, 600								16.8
5	Imazapic	4.8	na	55.0	24.4	3.4	3.8	0.0	0.0	0.0	17.9
6	Sulfosulfuron	70	na	22.5	5.1	0.6	0.0	0.0	0.0	0.0	
	Imazapic	9.6	400, 600								21.1
7	Sulfosulfuron	70	na	25.0	11.4	6.1	5.0	0.0	0.0	0.0	
	Imazapic	9.6	400, 500, 600, 700, 800								21.1
8	Imazapic	9.6	na	40.0	16.1	0.6	1.3	0.0	0.0	0.0	20.1
	P-Value			0.79	0.55	0.85	0.14	1	1	1	
	(alpha=0.05)										0.56

^Treatment 2 was a placeholder for a commercial standard PRE tank mix that was not applied in any of the experiments.
Two rows of the experiment experienced crop injury from glyphosate drift from a neighboring field early in development. Heavily injured plants were replaced with new transplants while the other plants grew out of the injury.
Means separated with one way analysis of variance followed by Tukey-HSD test in *agricolae* package in R. n=4.

Table 7. Phytotoxicity and yield from PICKIT tomato crop safety experiment 2, transplanted on May 29, 2019, near Davis, CA

				Percent Phytotoxicity								Yield kg/m^2 row
Trt.	**Treatment**	**Rate g ai/ha**	**GDD Appl.**	**6/6**	**6/20**	**7/3**	**7/17**	**7/31**	**8/14**	**8/28**	**9/10**	**9/19**
1	Control	na	na	1.3	5.0	0.0	0.0	0.0	0.0	0.0	0.0	21.2
2	Control 2^	na	na	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	20.7
3	Sulfosulfuron	37.5	na	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	22.1
	Imazapic	4.8	400, 500, 600, 700, 800									
4	Sulfosulfuron	37.5	na	0.0	3.8	10.0	0.0	0.0	0.0	0.0	0.0	18.4
	Imazapic	4.8	400, 600									
5	Imazapic	4.8	na	0.0	5.0	5.0	0.0	0.0	0.0	0.0	0.0	21.5
6	Sulfosulfuron	70	na	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	22.9
	Imazapic	9.6	400, 600									
7	Sulfosulfuron	70	na	0.0	3.8	2.5	0.0	0.0	0.0	0.0	0.0	21.3
	Imazapic	9.6	400, 500, 600, 700, 800									
8	Imazapic	9.6	na	0.0	3.8	2.5	0.0	0.0	0.0	0.0	0.0	22.4
	P-Value (alpha=0.05)			0.13	0.97	0.55	1	1	1	1	1	0.69

^Treatment 2 was a placeholder for a commercial standard PRE tank mix that was not applied in any of the experiments.
Means separated with one way analysis of variance followed by Tukey-HSD test in *agricolae* package in R. n=4.

Table 8. Phytotoxicity, height, and yield data from PICKIT tomato crop safety trial, transplanted on April 22, 2020, near Davis, CA.

				Percent Phytotoxicity					**Height cm**	**Yield kg/m^2 row**
Trt.	**Treatment**	**Rate g ai/ha**	**GDD Appl.**	**6/3**	**6/12**	**6/26**	**7/7**	**7/21**	**6/26**	**9/3**
1	Control	na	na	0.0	0.0	0.0	0.0	0.0	53	20.2
2	Control^	na	na	0.0	0.0	0.0	0.0	0.0	54	17.5
3	Sulfosulfuron	37.5	na	0.0	0.0	0.0	0.0	0.0	53	17.7
	Imazapic	4.8	400, 500, 600, 700, 800							
4	Sulfosulfuron	37.5	na	0.0	0.0	0.0	0.0	0.0	53	21.3
	Imazapic	4.8	400, 600							
5	Imazapic	4.8	na	0.0	0.0	0.0	0.0	0.0	52	19.0
6	Sulfosulfuron	70	na	0.0	0.0	0.0	0.0	0.0	55	19.9
	Imazapic	9.6	400, 600							
7	Sulfosulfuron	70	na	0.0	0.0	0.0	0.0	0.0	56	19.6
	Imazapic	9.6	400, 500, 600, 700, 800							
8	Imazapic	9.6	na	0.0	0.0	0.0	0.0	0.0	53	17.0
	P-Value (alpha=0.05)			1	1	1	1	1	0.38	0.65

^Treatment 2 was a placeholder for a commercial standard PRE tank mix that was not applied in any of the experiments.
Means separated with one way analysis of variance followed by Tukey-HSD test in *agricolae* package in R. n=4.

Table 9. Processing tomato injury data from two foliar imazapic dose response experiments conducted in 2020 near Davis, CA

	Experiment 1			Experiment 2		
	3 DAT	7 DAT	14 DAT	3 DAT	7 DAT	14 DAT
Rate g ai/ha	-------------% Plot with injured plants -------------					
4.8	0	0	0	0	0	0
9.6	0	0	0	0	0	0
18	0	0	0	0	0	0
36	0	0	0	0	0	0
72	0	0	0	0	0	0
P-Value (alpha=0.05)	1	1	1	1	1	1

Experiment 1 application on 7/7/20 and experiment 2 application on 7/21/20. Means were not statistically different ($p < 0.05$). n=4.

Rotational Crop Safety Evaluations

In the 2019 tomato crop treated with the PICKIT herbicides, there was no treatment related phytotoxicity (data not shown) or differences in yield (Table 10). In the 2020 season, there was no phytotoxicity observed in fall-planted wheat (data not shown). There were no significant differences in height or fresh weight among treatments for sunflower, safflower, and kidney beans (Tables 11, 12). Melon biomass tended to be lowest following the sulfosulfuron treatments; however, due to plot variability, field bindweed and gopher pressure, and an application of rimsufluron before planting (not registered on melons), these differences cannot be definitively attributed to the PICKIT herbicide treatments (Tables 11, 12). Corn planted after sulfosulfuron at 1X and 2X rates had significantly lower fresh biomass than control treatments ($p = <0.001$), as well as appearing stunted and chlorotic at all three rates (0.5, 1X, 2X) (Tables 11, 12; Fig. 9)

Table 10. Effects of modified PICKIT treatments on a 2019 tomato crop as a part of a rotational crop study conducted near Davis, CA.

Trt	**Treatment**	**Rate g ai/ha**	**Application**	**GDD Appl.**	**Tomato Yield kg/m row**
1	Control	na	na	na	20.3
2	Sulfosulfuron 0.5X	18.75	PPI	na	20.1
3	Sulfosulfuron 1X	37.5	PPI	na	18.7
4	Sulfosulfuron 2X	70	PPI	na	19.3
5	Imazapic	4.8	CHEMx5	400, 500, 600, 700, 800	14.7
6	Imazapic	9.6	CHEMx5	400, 500, 600, 700, 800	15.6
7	Imazamox	9.6	CHEMx5	400, 500, 600, 700, 800	19.9
8	Imazapyr	9.6	CHEMx5	400, 500, 600, 700, 800	17.2
9	Imazethapyr	9.6	CHEMx5	400, 500, 600, 700, 800	17.2
	P-Value (alpha=0.05)				0.31

Means separated with one way analysis of variance followed by Tukey-HSD test in *agricolae* package in R. n=4.

Table 11. Mean 2020 rotational crop heights in the season following 2019 herbicide treatments in tomato for management of branched broomrape in California.

Trt	**Treatment**	**Rate g ai/ha**	**Wheat***	**Corn**	**Safflower**	**Sunflower**	**Beans**	**Melon**
			--------------------------------	--------------------------------	**Height (cm)**	--------------------------------		
1	Control	na	na	127.2a	82.0	82.8	37.1	19.5abc
2	Sulfosulfuron 0.5X	18.75	na	109.4ab	85.9	88.1	36.8	17.1bc
3	Sulfosulfuron 1X	37.5	na	62.1bc	77.0	84.6	37.6	16.5c
4	Sulfosulfuron 2X	70	na	45.3b	81.8	78.2	38.9	11.9d
5	Imazapic	4.8	na	120.8a	82.0	82.8	38.6	18.7abc
6	Imazapic	9.6	na	128.8a	83.8	82.3	37.3	20.7abc
7	Imazamox	9.6	na	163.4a	83.3	91.4	38.4	22.4a
8	Imazapyr	9.6	na	131.9a	80.3	81.8	36.3	21.3ab
9	Imazethapyr	9.6	na	129.1a	81.5	74.7	39.4	18.0abc
	P-Value (alpha=0.05)			<0.001	0.91	0.29	0.86	<0.001
	MSD			54.3	na	na	na	4.6

*Visual crop injury ratings for wheat were taken rather than height (data not shown), and there was no injury in any plots.
Data were analyzed using a one-way analysis of variance and Tukey-HSD in the *agricolae* package in R. Means followed by the same letter within a column are not statistically different according to Tukey's test ($p < 0.05$). MSD= minimum significant difference. n=4.

Table 12. Mean 2020 rotational crop aboveground fresh biomass in the season following 2019 herbicide treatments in tomato for management of branched broomrape in California.

Trt	Treatment	Rate g ai/ha	Wheat*	Corn	Safflower	Sunflower	Beans	Melon
			---------------- Fresh biomass weight (kg) per meter of row --------					
1	Control	na	na	5.6a	2.7	6.8	1.2	2.8a
2	Sulfosulfuron 0.5X	18.75	na	4.3ab	3.5	6.5	1.5	1.5ab
3	Sulfosulfuron 1X	37.5	na	1.4bc	3.5	5.8	1.3	0.9ab
4	Sulfosulfuron 2X	70	na	1.1c	2.8	6.3	1.2	0.2b
5	Imazapic	4.8	na	5.0a	3.3	5.9	1.4	2.2ab
6	Imazapic	9.6	na	5.0a	3.2	5.7	1.3	2.1ab
7	Imazamox	9.6	na	6.8a	3.1	6.1	1.4	2.6ab
8	Imazapyr	9.6	na	4.7a	3.2	6.1	1.6	2.2ab
9	Imazethapyr	9.6	na	5.2a	3.0	6.2	1.5	2.3ab
	P-Value (alpha=0.05)			<0.001	0.69	0.88	0.85	0.03
	MSD			3.1	na	na	na	2.5

*Visual crop injury ratings for wheat were taken instead of weight (data not shown), and there was no injury in any plots.
Data were analyzed using a one-way analysis of variance and Tukey-HSD in the *agricolae* package in R.
Means followed by the same letter within a column are not statistically different according to Tukey's test ($p < 0.05$). MSD= minimum significant difference, ns= not significant.

PICKIT Efficacy Evaluation

Broomrape emergence was first observed in late May of 2020 and continued steadily until the termination of the experiment in late July (Fig. 8). There was continued emergence throughout the trial period, with no apparent germination flushes. Throughout the plot area, there were several apparent “hot” zones of higher broomrape emergence, as well as several “cold” zones with somewhat lower emergence (Fig. 8). Individual broomrape cluster numbers per 30-meter plot ranged from 0 to 58, with only one plot out of 48 having no broomrape emergence. Mean broomrape cluster numbers from PICKIT treatments (C, D, E, F, G, H, I, J, K) were not significantly different from one another but were lower than non-PICKIT treatments (A, B, L) (Fig. 10).

PICKIT treatments F and H upper limit values of a 3-parameter log-logistic function were significantly lower than all non-PICKIT treatments, while treatment C (1X sulfosulfuron/imazapic 1X x5), D (1X sulfosulfuron/imazapic x2), E (1X foliar imazapic x2), G (2X sulfosulfuron/imazapic x5), I (1X sulfosulfuron/imazamox x5), J (1X sulfosulfuron/imazapyr x5), and K (1X sulfosulfuron/imazethapyr x5) were significantly lower than 2 of the 3 non-PICKIT treatments, treatment B (untreated check 2) and L (rimsulfuron). ED50 values from a 3-parameter log-logistic function were not significantly different among treatments which indicates no clear treatment-related acceleration or delay in broomrape emergence (Table 13).

Table 13. Effect of chemigation treatments on predicted value of broomrape emergence in a tomato field trial from a 3-parameter log logistic model using *drc* package in R.

Trt	Treatment Name	Rate g ai/ha	GDD Appl	b(slope*) +/- 95 CI	d(upper lim) +/- 95 CI	e(ed50) +/- 95 CI
A	Control	na	na	-8.5 +/-6.5	20.5 +/-7.5	92.6 +/-11.8
B	Control 2	na	na	-12.5 +/-3.4	47.7 +/-4.1	94.0 +/-2.2
C	Sulfosulfuron Imazapic	37.5 4.8	na 400, 500, 600, 700, 800	-8.5 +/-6.5	20.5 +/-7.5	92.6 +/-11.8
D	Sulfosulfuron Imazapic	37.5 4.8	na 400, 600	-7.9 +/-12.8	15.2 +/-11.4	89.6 +/-25.6
E	Imazapic	4.8	na	-7.7 +/-22.3	11.8 +/-12.9	85.3 +/-37.6
F	Sulfosulfuron Imazapic	70 9.6	na 400, 500, 600, 700, 800	-13.3 +/-13.1	5.2 +/-1.5	90.4 +/-8.2
G	Sulfosulfuron Imazapic	70 9.6	na 400, 600	-14.2 +/-9.1	18.0 +/-3.6	94.3 +/-5.3
H	Imazapic	9.6	na	-12.3 +/-20.1	7.6 +/-2.5	73.8 +/-12.0
I	Sulfosulfuron Imazamox	37.5 4.8	na 400, 500, 600, 700, 800	-10.4 +/-19.5	17.7 +/-12.1	92.4 +/-20.0
J	Sulfosulfuron Imazapyr	37.5 4.8	na 400, 500, 600, 700, 800	-7.6 +/-6.8	18.1 +/-6.9	86.2 +/-13.5
K	Sulfosulfuron Imazethapyr	37.5 4.8	na 400, 500, 600, 700, 800	-8.4 +/-11.7	17.1 +/-9.7	88.9 +/-18.8
L	Rimsulfuron	7.2	na	-8.3 +/-4.2	49.9 +/-11.2	90.2 +/-7.4

* The slope of the dose-response curve at ED50 has the opposite sign as compared to the sign of the parameter b (Kniss and Streibig 2018).

Discussion

Crop Safety Evaluations

After two field seasons and three studies, crop safety for the imidazolinone and sulfonylurea herbicides utilized in the PICKIT system appears acceptable at both the proposed rate structure and two times the proposed rate structure in California processing tomato. These results confirm the crop safety reported for the PICKIT program in Israel. Sulfosulfuron is registered in California under the trade name Outrider for non-crop use. Imazapic is not currently registered in California and faces a difficult registration pathway in California, so future research will focus on another imidazolinone herbicide, imazamox, which has a more favorable registration pathway. Crop safety studies will need to be repeated using chemigated imazamox and will be conducted in 2021.

Rotational Crop Safety Evaluation

Based on this initial rotational crop safety experiment, there were few indications of problems related to the imidazolinone herbicides applied five times via chemigation at the proposed 2x use rate. There was some early season stunting and chlorosis observed with sulfosulfuron in sunflower, but the plants grew out of this injury. There were some indications of crop safety concerns for PPI sulfosulfuron treatments, primarily for corn and melon. Seeding across all crops was inconsistent and denser than commercially planted stands. The field was treated with rimsulfuron before planting corn, safflower, sunflower, beans, and melon. Rimsulfuron is not registered on melons, so differences in melon plant height and weight cannot be attributed solely to PICKIT herbicide treatments. Heavy field bindweed and gopher pressure also contributed to the variability within and among treatments. If the herbicides utilized in the PICKIT system are registered in California, tomato growers will have to adjust crop rotations based on the plant back restrictions associated with sulfosulfuron (Anonymous, 2016). Given the importance of tomato in this cropping system, such rotational crop restrictions might be acceptable to growers impacted by branched broomrape. Only a single rotational study was conducted, and more experiments should be conducted to further inform growers and the industry of the specific crop safety concerns with this broomrape management approach.

PICKIT Efficacy Evaluation

Currently, the economic and action threshold for branched broomrape in California is any detection of the parasitic plant. With the exception of a single plot, all of the treatment plots had broomrape (Fig. 8). The PICKIT treatment plots had fewer broomrape clusters on average than non-PICKIT plots, though the late season foliar applied treatments (12 June and 25 June) should not have had affected early season emergence and had some of the lowest cumulative number of broomrape clusters (Treatment H). This is likely due to an uneven distribution of broomrape, resulting in some "hot" areas of the field with high broomrape emergence and "cold" areas with relatively low emergence. The experimental blocking was arranged based on reports of higher broomrape density observed by the grower the previous year in the south edge of the field. However, likely due to cultivation patterns, there were some areas of some beds with lower or higher broomrape density than adjacent beds. While the experiment was blocked to reduce variation due to factors like this, more experiments must be done to determine the efficacy of each individual treatment. Broomrape locations were mapped with GPS in 2020, and this mapping data will be used in subsequent experiments at this location to inform blocking decisions (Fig. 8). PICKIT treatments had some effect on broomrape emergence, generally reducing emergence compared to non-PICKIT treatments. However, more studies will need to be conducted to determine the relative efficacy of individual PICKIT treatments among each other and to further refine rates and treatment protocols for control of branched broomrape.

The PICKIT decision support system is based on a growing degree day model developed using Egyptian broomrape (*Phelipanche aegyptiaca*). It has been noted by PICKIT researchers that branched broomrape and Egyptian broomrape do not share the exact same phenology (Galaz, J.C., personal communication, July 27, 2020). Future research will examine the effects of alternate timing of chemigation treatments to address the temporal difference in development between the two species.

Next steps

Further research on branched broomrape control strategies in California processing tomato will continue. Due to the difficult regulatory pathway for imazapic in California, future research will focus on imazamox, which already has a registration in California on alfalfa (Anonymous, 2010). A project was initiated in early 2021 in Chile to evaluate the potential of imazamox as a chemigation herbicide in addition to informing decisions for mid-2021 research in California.

As of summer of 2021, there have been several additional formal reports of broomrape infested commercial tomato fields. The problem is growing, and while eradication may still remain the goal for many, management tools will need to be developed if this weed were to become widespread and or de-regulated as a quarantine pest.

Figure 1. CO_2 injection system used in 2020 crop safety and efficacy studies. Chemigation mix (11 L) was pressurized and injected into layflat hose. Valves at each plot were opened or closed to control which plots received treatments.

Figure 2. Valved connections at each plot allowed two replicates to be treated at once. A valve was located at the end of the layflat line to flush line in between treatments.

Figure 3. Hanson lab members harvest all fruit from a one square meter section of row of a 2019 crop safety study at the end of the season.

Figure 4. Corn, sunflower, safflower, melon, and bean planted in 2020 in a split plot design with four replications. Each row had six crops planted in 9 m sections.

Figure 5. Broomrape clusters emerged over time marked with different colored flags. Each color represents a different week of broomrape cluster emergence.

Figure 6. Broomrape clusters at different development stages. Broomrape emergence was continuous throughout the season.

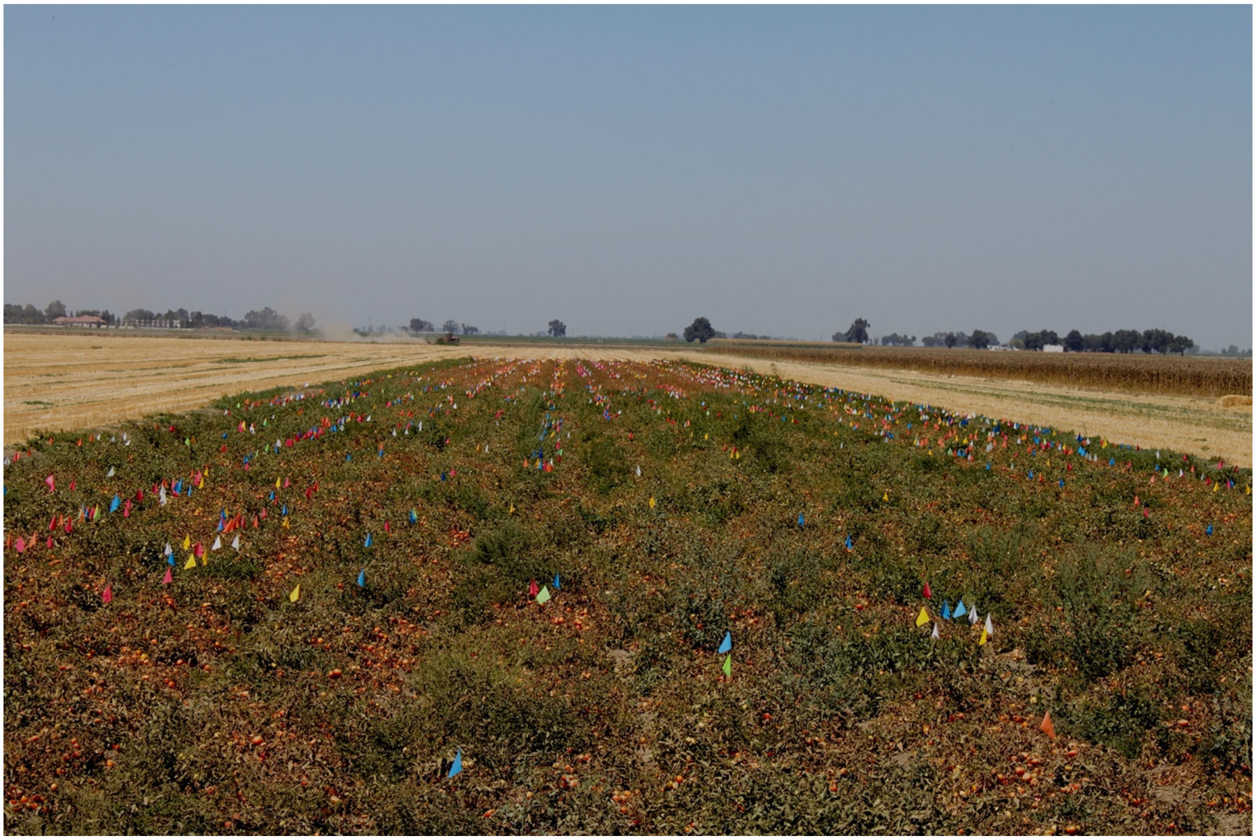

Figure 7. Infested 0.9-hectare field at commercial tomato maturity with over 2700 marked broomrape clusters.

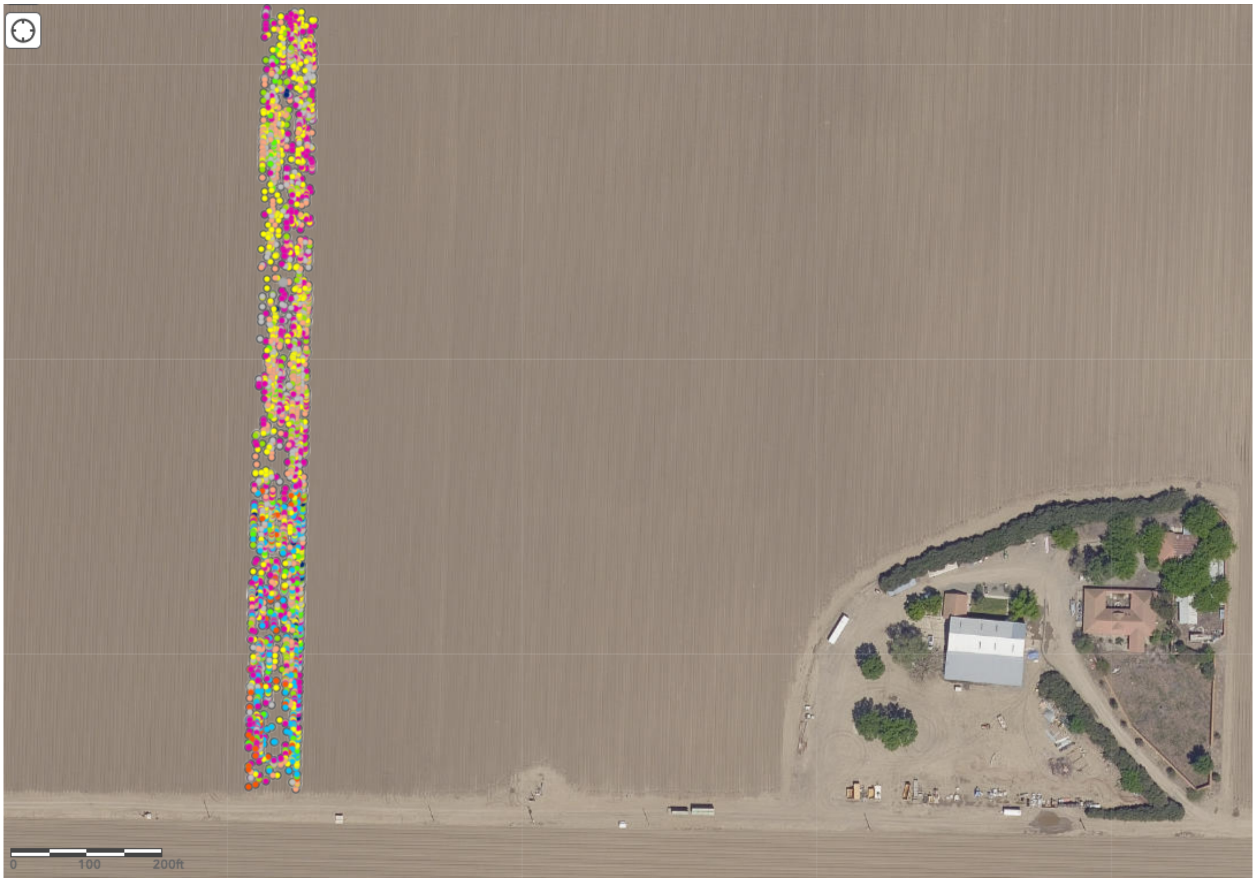

Figure 8. A color-coded map created in ArcGIS.com. Each week of emergence is indicated by a color. The south half of the field was where herbicide treatments were conducted. The north half of the field will be used for future research. Further study designs will be informed by broomrape distribution indicated in this map, along with potential spatial analysis of broomrape emergence and spread over multiple seasons.

Figure 9. Corn exhibiting stunting after sulfosulfuron applications during the previous season's tomato crop. Corn experienced stunting at all three rates of sulfosulfuron (0.5X, 1X, 2X PICKIT rates).

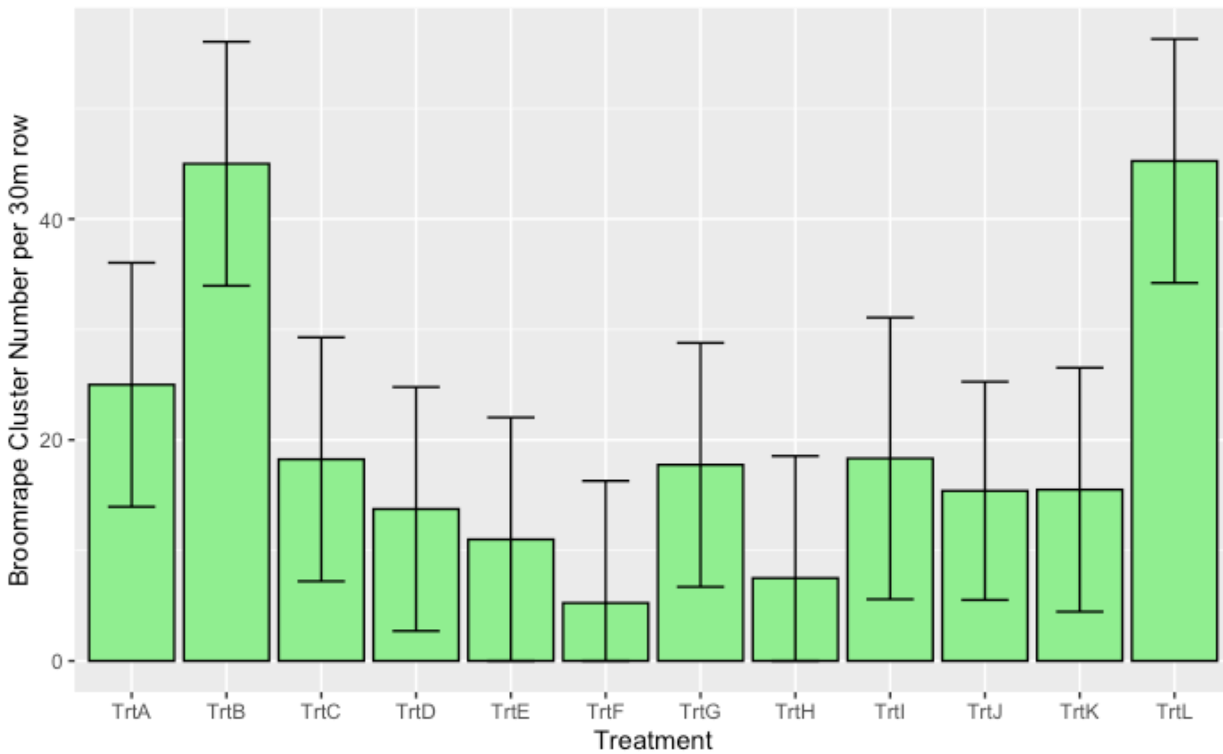

Figure 10. Effect of chemigation treatments (Table 5) on cumulative number of branched broomrape clusters at tomato maturity in a commercial tomato field near Woodland, CA, in July 2020.

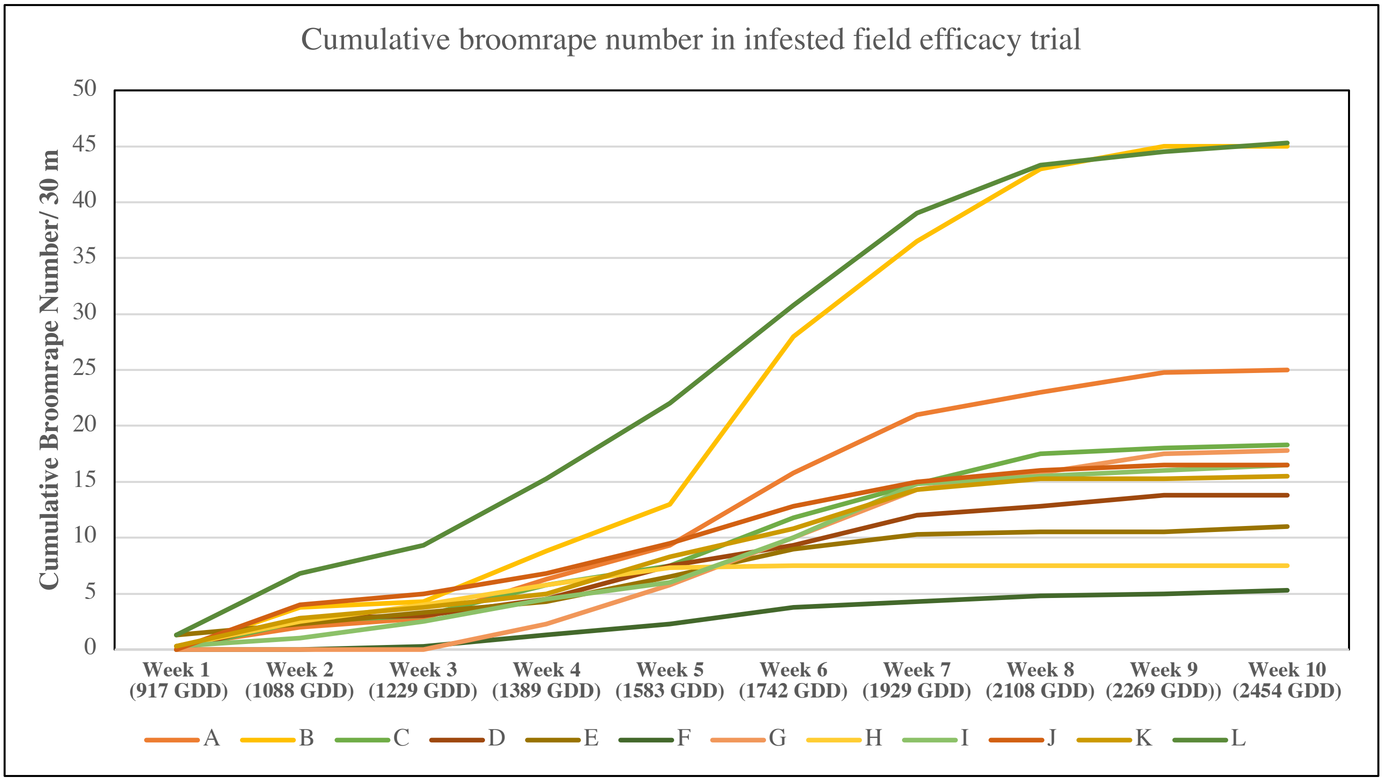

Figure 11. Effect of chemigation treatments on cumulative emergence of branched broomrape in a commercial tomato field near Woodland, CA in 2020. Treatments began at 400 GDD and the last treatment was at 800 GDD.

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Appendix

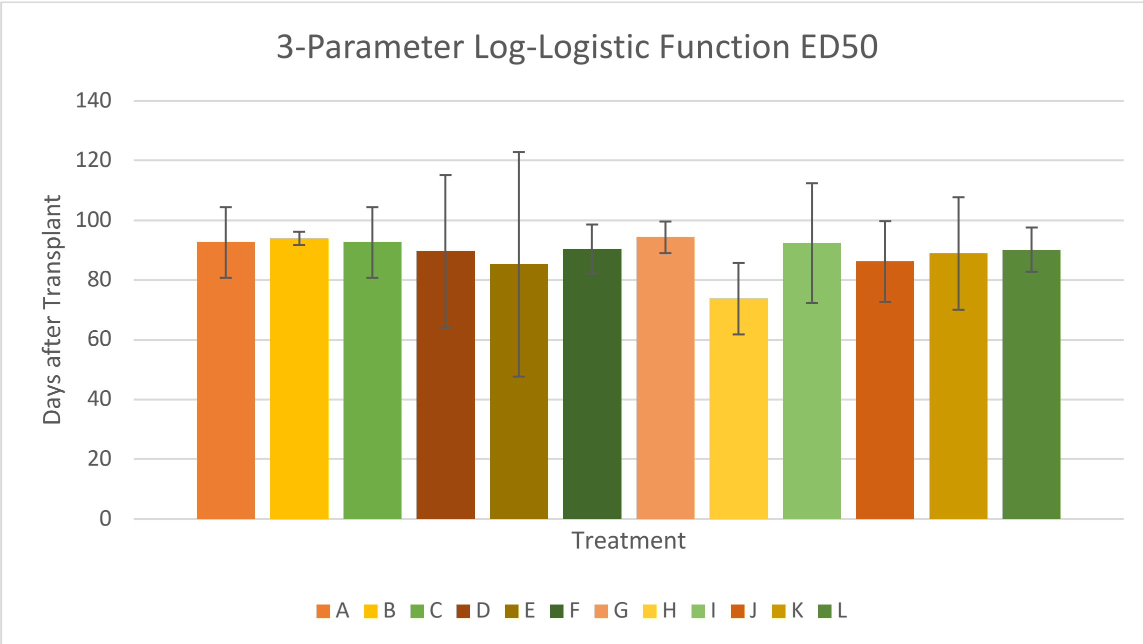

Figure A1. ED50 from 3-parameter log-logistic function. Error bars represent 95% confidence interval (Table 5).

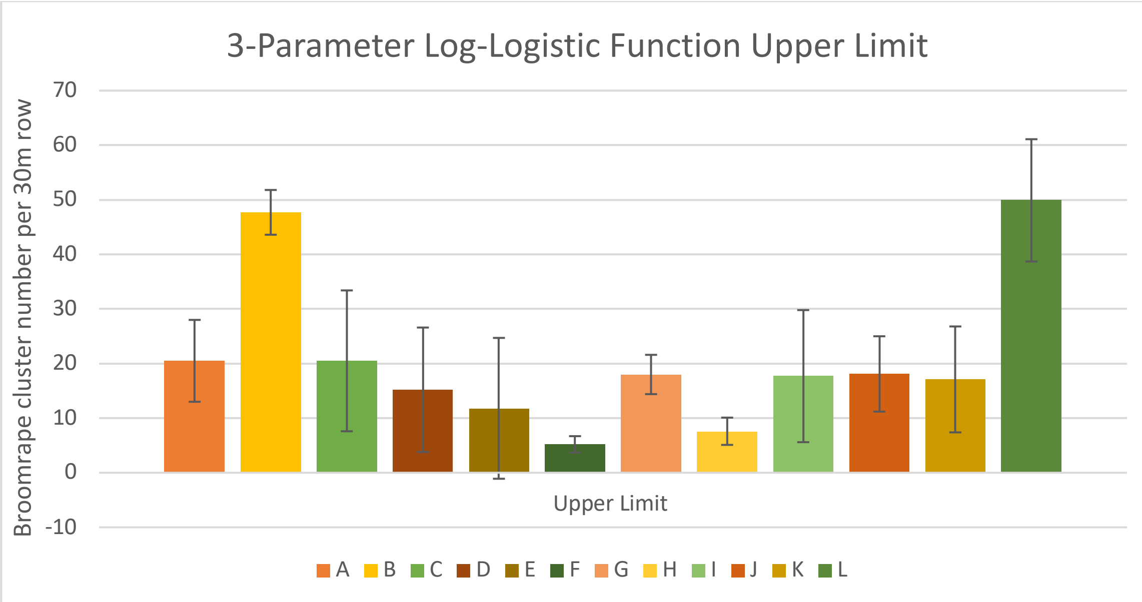

Figure A2. Upper limit from 3-parameter log-logistic function. Error bars represent 95% confidence interval .

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