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To uproot or bury? Modeling selectivity of in-row mechanical cultivation

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Abstract

Selectivity, the ability to kill weeds without killing the crop, is a challenge for in-row mechanical cultivation, especially in slow-growing crops like carrots [*Daucus carota* L. ssp. *sativus* Hoffm. 'Bolero']. To gain insight into the optimal tool type and timing for in-row cultivation of different weed species, we adapted an existing model ("Kurstjens model") to predict "potential efficacy" (PE)—the greatest weed mortality attainable at a given level of crop mortality—based on weed anchorage force and height data, which serve as proxies for tolerance to uprooting and burial. We parametrized the baseline model using data for carrots and five weed species at early growth stages and used the model to predict the PE of idealized tools that bury or uproot in combination with various cultural practices. Under baseline model assumptions, tools that bury had greater PE for grass weeds, and tools that uproot had greater PE for broadleaves. Combining or "stacking" tools that uproot with those that bury had minimal impact on predicted PE for individual weed species, but increased PE on mixed grass–broadleaf weed communities compared with single-tool mechanisms of action. Cultural practices (e.g., stale seedbedding and cultivar choice) that increased carrot anchorage force and height relative to weeds at the time of cultivation greatly increased PE for both mechanisms of action. Our model provides a useful method for predicting the optimal tool mechanism of action and timing for any weed–crop combination.

Introduction

Despite the central role of mechanical cultivation (or "physical weed control" based on soil disturbance) for managing weeds in many crops, relatively little scientific guidance is available to determine optimal tools and timing to maximize efficacy while avoiding crop damage. The selectivity of weed management tools—their ability to kill weeds without damaging the crop—is particularly challenging for mechanical cultivation tools applied to the in-row (or "intrarow") zone of slow-growing direct-seeded vegetable crops such as carrots [*Daucus carota* L. ssp. *sativus* Hoffm. 'Bolero'] (Ascard and Bellinder 1996; Champagne 2022; Tilton 2018). In these crops, growers often have multiple tool options, but lack information needed to determine which will provide greatest selectivity for a given weed–crop–soil combination (Gallandt et al. 2018).

Simulation models that predict weed and crop mortality based on their relative tolerance to forces applied by cultivation tools can provide insight on the optimal type and timing of cultivation to maximize weed mortality while avoiding crop injury. For example, Kurstjens et al. (2004) developed a model (hereafter referred to as "Kurstjens model") to predict the selectivity of mechanical weed control tools that apply uprooting forces based on empirical measurements of crop and weed root anchorage forces that relate directly to tolerance to uprooting. Their model uses the measured frequency distribution of anchorage forces of crop and weed populations relative to the distribution of uprooting forces applied by the tool to determine the percentage of crops and weeds that would die, and hence the tool's selectivity. The Kurstjens model provides a useful framework for comparing tactics for improving selectivity, including those that increase crop anchorage force relative to weeds and those that involve adjustments in tool design or tool settings that increase the precision of uprooting forces applied by the tool (Gallandt et al. 2018).

Because mechanical cultivation tools may kill weeds through multiple mechanisms of action (e.g., slicing, burial, or uprooting), predicting the optimal tool for a given crop–weed combination may benefit from characterization of multiple plant traits that promote tolerance to those mechanisms of action. While the Kurstjens model predicts selectivity of tine weeders that work by uprooting, they suggest that the same basic framework could be used to evaluate tools with other mechanisms of action. For example, in carrots and other row crops, several mechanical cultivators (e.g., hilling disks) move soil into the crop row to bury weeds. For improved understanding of these tools, we hypothesized that traits affecting the relative tolerance of crops and weeds to burial (e.g., height) could be characterized and integrated into a simulation model to predict selectivity. In theory, simultaneous knowledge of crop and weed tolerance to multiple mechanisms of action over time, coupled with knowledge of the forces applied by various tools, should provide insight into which tools will maximize selectivity at different stages of crop production.

Given the importance of burial as a critical mechanism of action in mechanical cultivation, knowledge regarding crop and weed tolerance to burial is critical for modeling and understanding selectivity. Although plants differ in their tolerance to burial, and recovery from burial depends on soil characteristics (Baerveldt and Ascard 1999; Mohler et al. 2016), for most annual plants at early growth stages, covering the tallest plant part completely is usually lethal (Merfield et al. 2020). This important observation suggests that a modified version of the Kurstjens model, based on the relative heights of crops and weeds (analogous to anchorage force) and the depth of burial of the tool (analogous to the uprooting force) could be developed to predict selectivity of tools that bury.

Modeling the potential selectivity of tools with different mechanisms of action may also provide insights into the circumstances under which "tool stacking"—combining different tools in sequence—can improve selectivity. Empirical studies demonstrate that stacking of cultivation tools with different mechanisms of action can improve the efficacy and selectivity of mechanical cultivation of competitive crops such as field corn (*Zea mays* L.) (Brown and Gallandt 2018). However, the impact of tool stacking on selectivity in more sensitive crops like carrots can be quite variable, and selectivity strongly depends on both the tool combinations used and the target weed species (Brown and Gallandt 2018; Tilton 2018). To our knowledge, few studies provide a mechanistic framework for understanding such variation in stacking performance to help identify optimal mechanical tool combinations given different characteristics of weeds and crops.

Simulation models may also provide useful information on the interactive effects of cultural practices and mechanical cultivation on selectivity, particularly in sensitive vegetable crops like carrots. Weeds are particularly challenging for organic production of carrots (Peruzzi et al. 2007), which represented 18% of carrots grown in the United States in 2021 (USDA-NASS 2021). Due to their slow emergence and early growth, carrots are vulnerable not only to early competition from weeds, but also to injury from weed management tools used to control them (Colquhoun et al. 2017; Fogelberg and Dock Gustavsson 1998). To address this challenge, growers may use preventative and cultural practices, including stale seedbedding and competitive cultivars (Peruzzi et al. 2007; Tilton 2018) in combination with frequent early cultivation, to maintain a crop size advantage. Mechanical cultivation options in carrots include cutaway disks, finger weeders, torsion weeders, sweeps, and tine harrows, which vary in their mechanism of action (Gallandt et al. 2018; Pannacci et al. 2017). Unfortunately, successful selective cultivation with these tools varies considerably across studies (Champagne 2022; Fogelberg 1999; Tilton 2018) likely due to variation in tool settings, soil conditions, and the relative tolerance of crops and weeds to those tools (Gallandt et al. 2018). As a result, growers have little evidence-based guidance on the optimal tools and timing.

To our knowledge, few if any studies have systematically measured both height and anchorage force of crops and associated weeds to better understand their relative sensitivity to uprooting and burial from mechanical cultivation over time. Our overall goal was to use this information, in combination with a simulation model, to gain insight into the optimal tools and timing of mechanical cultivation, as well as their interactions with various cultural practices affecting the relative height and anchorage force of crops and weeds. Our primary objectives were to (1) develop and parameterize a model to simulate the "potential efficacy" (PE; maximum weed mortality attainable for a fixed level of acceptable crop mortality) of mechanical cultivation tools that uproot or bury weeds; and (2) use the model to simulate the impacts of tool choices and cultural practices on PE, using empirical data for carrots and five associated weeds as a case study. We hypothesized that (1) the simulated PE of mechanical cultivation in carrots would vary based on the mechanism of action (burial or uprooting), timing of cultivation, and weed species; (2) cultural practices that increase the anchorage force or height of carrots relative to weeds (e.g., stale seedbedding and seed quality) would improve the PE of tools; and (3) combining or stacking tool mechanisms of action would improve PE, but those benefits would vary with timing and with the composition of the weed community. The broader practical purpose of this work is to help growers select optimal tools and associated cultural practices to improve the selectivity of their mechanical cultivation.

Materials and Methods

Model Overview and Comparison to Kurstjens Model

Our simulation model utilizes empirical data inputs (anchorage force and height of crops and weeds) and simple mechanistic assumptions to predict the PE of mechanical cultivation tools. Our model shares several key features of the Kurstjens model (Kurstjens et al. 2004). In particular, key model inputs include empirical data on the frequency distribution of weed and crop anchorage forces at multiple sampling dates. Crop and weed mortality at each sampling date are simulated assuming an idealized mechanical cultivation tool that simultaneously imposes precise uprooting forces to all crops and weeds to maximize selectivity. Mortality is calculated based on the simple assumption that individual seedlings die if and only if they have anchorage forces less than the uprooting force applied by this idealized tool. Finally, the optimal uprooting force is calculated by maximizing "selectivity," which is calculated based on crop and weed mortalities.

However, our model differs from the Kurstjens model in several ways. First, rather than calculating "potential selectivity," we model "potential efficacy" or "PE," which we define as the maximum achievable weed mortality given a *fixed level* of acceptable crop mortality. This approach reduces ambiguity and confusion associated with varying definitions of "selectivity," including those used by Kurstjens et al. (2004) and others (Rasmussen 1992; Tilton 2018), which entail trade-offs in practical interpretation discussed elsewhere (e.g., Gallandt et al. 2018; Rueda-Ayala et al. 2010; Tilton 2018). Our focus on PE is also based in part on conversations with growers of high-value vegetable crops like carrots, whose primary concern when choosing and calibrating mechanical cultivation tools is often avoidance of crop damage. These growers typically have in mind a threshold of acceptable crop mortality or injury that varies based on various factors including the value of the crop and the perceived relationship between crop density and yield. Because our model was developed with the ultimate goal of helping growers choose the appropriate tool and timing for success, we constructed the model with acceptable crop mortality as an important baseline parameter. Our model also differs from the Kurstjens model because we explore differences in PE for two common tool mechanisms of action, rather than focusing on deviations between potential and actual outcomes of a single tool and mechanism of action. By extending the Kurstjens model to explore the relative PE of tools that bury versus those that uproot, we are able to evaluate which tools and mechanisms of action are most likely to benefit growers given different crop–weed conditions. Finally, in contrast to the Kurstjens model, which fits functions to empirical anchorage force data to predict crop and weed mortality, we use actual anchorage force and height data to simulate potential crop and weed mortality.

Modeling PE

Following an approach conceptually similar to that used in the Kurstjens model, we use experimental data on the anchorage forces and heights of populations of weeds and crops (summarized in Table 1, with specific example in Figure 1) as model inputs to calculate PE at a given time through a series of steps coded in R (R Core Team 2022; Appendix A). First, we input the ordered sets of measured anchorage force and height data for the crop (F_c, H_c) and weeds (F_w, H_w) for each sampling date:

$$F_c = \{F_{c1}, \ldots, F_{cm}\} \quad [1]$$

$$H_c = \{H_{c1}, \ldots, H_{cm}\} \quad [2]$$

$$F_w = \{F_{w1}, \ldots, F_{wn}\} \quad [3]$$

$$H_w = \{H_{w1}, \ldots, H_{wn}\} \quad [4]$$

where m is the total number of individual crop seedlings sampled; n is the number of individual weeds sampled; F_{ci} and F_{wj} represent the root anchorage forces and H_{cj} and H_{wj} the heights of the individual crops (i ranging from 1 to m) and weeds (j ranging from 1 to n), arranged in order from lowest to highest. Using crop input data for each sampling date (F_c and H_c), we calculate the threshold uprooting force (F^*) and burial height (H^*) that would limit crop mortality to 5%. For simulations of tools that uproot, F^* is assumed to be equal to the anchorage force of the ath individual crop plant (F_{ca}), such that 5% of the plants have equivalent or lower anchorage forces (Equation 5). Similarly, for simulations of hilling, the threshold burial height (H^*) that limits crop mortality to 5% is equal to the height of the bth (H_{cb}) individual, such that 5% of the plants have equivalent or shorter height than plant b (Equation 6):

$$F^* = F_{ca} | a = 0.05 \times m \quad [5]$$

$$H^* = H_{cb} | b = 0.05 \times m \quad [6]$$

For example, in cases where the heights of 60 individual crop seedlings are used ($m = 60$), the threshold height (H^*) is equivalent to the height of the third shortest individual ($b = 0.05 \times 60 = 3$). Note that in rare cases where two crop plants have exactly the same height H^* or anchorage force F^*, simulated crop mortality may exceed 5% slightly (e.g., simulated crop mortality is 6.7% if $m = 60$ and two crop plants have the same height H^*).

Once the threshold uprooting force (F^*) and burial height (H^*) are determined, the next step is to estimate weed mortality at those thresholds, and hence the PE of uprooting (PE_U) and burial (PE_B) for each weed species. To do so, we assume that weeds subject to uprooting will die if and only if they have anchorage forces less than F^*, and those subject to burial will die if and only if they have heights less than H^*. We define $F_{w\_uprooted}$ as the subset of anchorage forces of all weeds (F_w) with anchorage force less than F^* (Equation 7) and H_{w_buried} as the subset of heights of all weeds (H_w) with heights less than H^* (Equation 8):

Table 1. Mean and SD of height and anchorage force measurements of carrots and weeds used to parameterize baseline model using data collected from plants grown in greenhouses in East Lansing, MI, in 2021[a].

	Height											
	113 GDD		164 GDD		213 GDD		263 GDD		340 GDD		393 GDD	
Species	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	— cm —											
Carrot	0.28	0.12	2.24	0.50	2.86	0.52	3.70	0.62	5.69	1.08	8.01	1.58
Amaranthus cruentus	1.27	0.36	1.79	0.46	2.36	0.54	3.01	0.67	4.40	0.89	5.36	1.27
Chenopodium album	0.80	0.44	1.64	0.46	2.19	0.53	2.68	0.65	2.94	0.63	3.49	0.56
Digitaria sanguinalis	0.65	0.22	0.92	0.36	1.23	0.39	1.86	0.82	3.78	1.47	3.60	0.61
Brassica juncea	1.50	0.48	2.89	0.61	3.52	0.64	4.42	0.90	6.34	1.23	6.82	0.86
Setaria faberi	0.42	0.09	1.50	0.54	2.05	0.47	3.27	1.08	6.00	1.80	8.36	3.26
	Anchorage force											
	113 GDD		164 GDD		213 GDD		263 GDD		340 GDD		393 GDD	
Species	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	— N —											
Carrot	NA	NA	0.36	0.10	0.53	0.15	0.62	0.20	0.93	0.27	1.04	0.35
Amaranthus cruentus	0.23	0.10	0.23	0.07	0.34	0.09	0.42	0.10	0.78	0.22	0.92	0.43
Chenopodium album	NA	NA	0.21	0.07	0.24	0.06	0.29	0.08	0.40	0.15	0.58	0.23
Digitaria sanguinalis	NA	NA	0.20	0.07	0.26	0.09	0.32	0.08	0.41	0.18	0.33	0.05
Brassica juncea	0.46	0.17	0.59	0.13	0.86	0.19	1.28	0.40	2.38	0.59	3.17	0.55
Setaria faberi	NA	NA	0.30	0.08	0.39	0.09	0.50	0.15	0.73	0.24	0.89	0.35
	Leaf stage											
Species	113 GDD		164 GDD		213 GDD		263 GDD		340 GDD		393 GDD	
Carrot	C		C		C		C		C		C–1	
Amaranthus cruentus	C		C		C		C		C–1		1–2	
Chenopodium album	C		C		C		C		C–2		2	
Digitaria sanguinalis	C		1		1		1–2		1–2		1–2	
Brassica juncea	C		C		C–2		2		2–4		2–4	
Setaria faberi	C		C		1–2		1–2		2		2–4	

[a]Abbreviations: C, cotyledon; GDD, growing degree days (base temperature = 5 C); NA, not applicable.

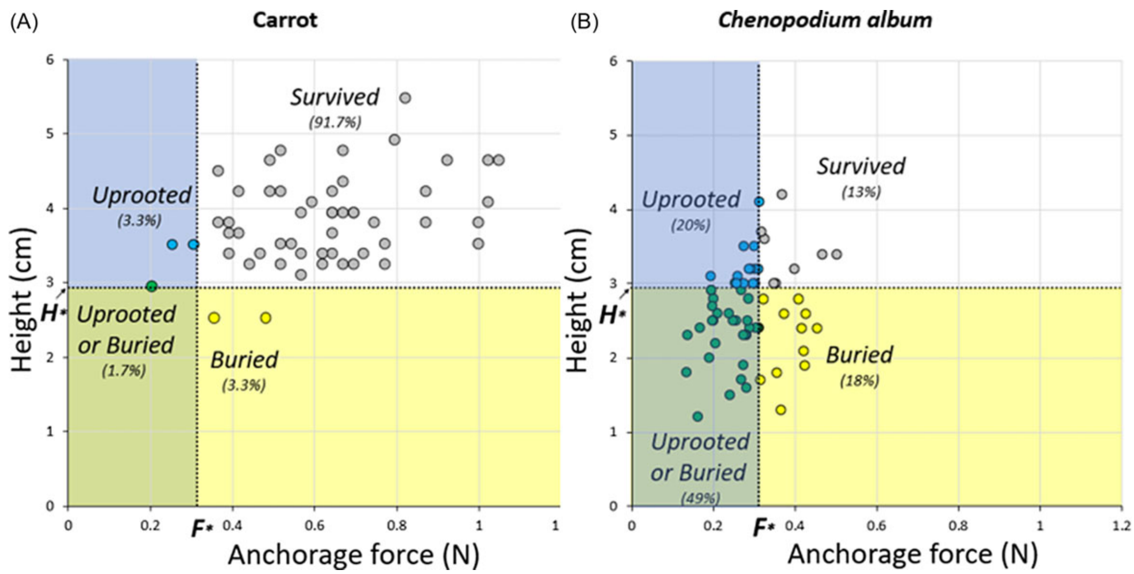

Figure 1. Anchorage force and height of 60 carrot (A) and 60 *Chenopodium album* (B) seedlings sampled at 263 growing degree days (GDD) after sowing. Under baseline model assumptions, H^* (2.9 cm) represents the threshold depth of burial and F^* (0.31 N) represents the threshold uprooting force that limit carrot mortality to 5%. When the population of *Chenopodium album* is subjected to burial depth H^*, 68% of seedlings would be buried (yellow and green regions). Likewise, when an uprooting force of F^* (0.31 N) is applied, 70% of *Chenopodium album* seedlings would be uprooted (blue and green regions). These mortality rates represent the potential efficacy (PE) of cultivation tools that bury (PE_B) or uproot (PE_U), respectively. Data collected in greenhouse trials in East Lansing, MI, in 2021.

$$F_{w\_uprooted} = \{F_{wj} \ \epsilon F_w | F_{wj} < F^*\} \quad [7]$$

$$H_{w\_buried} = \{H_{wj} \ \epsilon H_w | H_{wj} < H^*\} \quad [8]$$

The PE_U for a specific weed species at a specific timing is then defined as the number of individuals uprooted divided by the total number of individuals of that species, expressed as a percentage (Equation 9). Likewise, PE_B is defined as the percentage of weeds buried (Equation 10):

$$PE_U = \frac{count(F_{w\_uprooted})}{count(F_w)} \times 100 \quad [9]$$

$$PE_B = \frac{count(H_{w\_buried})}{count(H_w)} \times 100 \quad [10]$$

where $count(F)$ is the number of elements (individual plants) in each set. Using this procedure, we calculated PE_U and PE_B based on simulations for each of the five weed species at each of the six sampling dates under the set of baseline assumptions discussed in more detail in the following section.

Baseline Model Assumptions

Plant Tolerance to Uprooting and Burial

To calculate PE_U in our baseline model, we assume plants die if and only if they have an anchorage force less than the tool uprooting force (Equation 7). Similarly, we assume that for calculation of PE_B, plants are killed if and only if their height is less than the burial depth of the tool (Equation 8). These are useful simplifying assumptions that appear to hold true for many annual weed species (Habel 1954, Kees 1962, Koch 1964b as cited in Kurstjens and Perdok 2000; Merfield et al. 2020; Mohler et al. 2016).

Relative Time of Crop and Weed Emergence

For our baseline model, we assume that all plant species are the same age at the time of cultivation, as would be expected for early cultivation events where the crop is sown into a freshly tilled weed-free bed with ungerminated weed seeds. In other words, we calculate F^* and H^* from carrot data for a specific sampling date and apply those thresholds to weeds from the same sampling date to calculate PE_B and PE_U (Equations 1 to 10). In reality, the timing of weed emergence relative to crop emergence may vary considerably based on the weed species, depth of burial, soil temperature, and moisture conditions. Management practices, including the timing and type of bed preparation and herbicide use, can also greatly impact the timing of weed and crop emergence and their relative age at the time of cultivation events. In subsequent runs of our model, we evaluate the impact of these practices by varying assumptions regarding the relative time of crop and weed emergence.

Exploring Variations in Model Assumptions

Modeling Additive Effects of Tool Stacking on Weeds and Weed Communities

To model the effects of tool stacking—combining tools that uproot with those that bury—we first calculate the PE_U of uprooting for each weed species k ($PE_{U,k}$) using the anchorage force data for a particular sampling date (Table 1). Then, considering only the weeds that would have survived this simulated uprooting step (those with anchorage force greater than the uprooting force applied to achieve $PE_{U,k}$), we use height datasets from those surviving plants as our model input to determine the PE_B of burial *following* uprooting ($PE_{B',k}$) under the additional assumption that total crop mortality from both uprooting and burial is limited to 5%. To do so, we iteratively tested a range of values for crop mortality of uprooting and of burial following uprooting to determine the maximum weed mortality while ensuring the total crop mortality from both tools combined remained under 5%.

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Note that $PE_{B',k}$ is distinct from $PE_{B,k}$, which represents the PE of burial *in the absence* of a previous uprooting event. The PE of stacking tools on weed species k ($PE_{S,k}$) is then defined as follows:

$$PE_{S,k} = PE_{U,k} + PE_{B',k} \quad [11]$$

In other words, the PE of stacking for each species k, is assumed to be equivalent to the PE of uprooting plus the PE of burial *following uprooting*. This simplified "additive" assumption implies that there are no synergistic (or antagonistic) effects of uprooting on the subsequent efficacy of burial. In reality, uprooting forces applied by the first tool might injure an individual weed (or crop), thereby increasing its sensitivity to subsequent burial by a second tool (Brown and Gallandt 2018).

To gain insight into the effects of weed community composition on the impact of tool stacking, we ran simulations assuming various combinations of weed species. In these simulations, the PE of tool stacking on an entire weed community (PE_S) is calculated using the weighted sum of the PE of stacking for each weed species k over all n weed species in the community:

$$PE_S = \sum_{k=1}^{n} a_k \times PE_{S,k} \quad [12]$$

where a_k is the proportion of species k in the weed community. To illustrate this approach, we present results of the effects of tool stacking on both individual weed species and on a simple weed community consisting of an even mix of two species: common lambsquarters (*Chenopodium album* L.) (representative broadleaf weed) and giant foxtail (*Setaria faberi* Herrm.) (representative grass weed). We also calculate the "benefit of stacking" as the difference between PE_S and the PE of the best alternative single mechanism of action (maximum of PE_U and PE_B).

Simulated Effects of a Stale Seedbed on PE

To gain insight into the impacts of stale (or "false") seedbed practices on PE of burial and uprooting, we incorporate a lag time between carrot and weed emergence in our simulations. This assumption is based on common grower practice of waiting until 1 to 2 d before anticipated crop emergence to flame weed or apply herbicides to emerged weeds. When executed successfully, this stale seedbed approach not only reduces the density of weeds emerging with the crop, but also delays their time of emergence relative to the crop and thus reduces their relative size and competitive ability with the crop (Bond and Grundy 2001). In our stale seedbed simulation, we assume a lag-time of 100 growing degree days (GDD) between carrot and weed emergence based on the time required for carrots to emerge in our greenhouse study.

For example, instead of using the set of anchorage forces of weeds and crop from the same growing degree day (g) as inputs for the simulation, we use the set of anchorage forces for the weed from day g with the set of anchorage forces of the crop from sample day $g - 100$. In effect, this assumption increases the anchorage force and height of crops relative to weeds, creating conditions for increased PE.

Simulated Effects of Crop Cultivar and Seed Quality on PE

To better understand how differences in carrot cultivar or seed quality affect PE, we vary our simulation input mean carrot height and anchorage force in 10% increments from 50% smaller to 50% larger than our baseline assumptions at the time of simulated cultivation at 263 GDD from seeding, and calculate changes in PE for each weed species. This range of variation is based on empirical data on carrot cultivar and carrot seed-size effects on seedling height and anchorage force (Connors 2022; Tilton 2018). For example, Tilton (2018) found that Bolero seedlings were 22% to 53% larger than those of other cultivars, including 'Danvers' and 'Napoli' at the 1 true-leaf stage. Connors (2022) found at 22 d after seeding (DAS) that carrots from large seed-size classes had 20% greater anchorage force and 12% greater height than those from small seed-size classes.

Plant Anchorage Force and Height

Anchorage force and height data used to parameterize the baseline model (Table 1) were taken from plants grown at Michigan State University's Plant Science Greenhouses in East Lansing, MI, from September 21 to October 7, 2021 (Run 1) and from November 4 to 26, 2021 (Run 2). Details are provided in Connors (2022). In brief, six plant species were grown from seed, including one crop (carrot), two "surrogate weeds" (condiment mustard [*Brassica juncea* (L.) Czern. 'Mighty Mustard'] and red amaranth [*Amaranthus cruentus* L. 'Red Spike']), and three weed species (*C. album*, *S. faberi*, and large crabgrass [*Digitaria sanguinalis* (L.) Scop.]). Surrogate weeds were included due to their ease of establishment and use in related field studies to mimic typical broadleaf weed species. Plants were grown in 10.5-cm-diameter round plastic pots filled with a 3:2:1 mixture of field soil (Spinks loamy sand, sandy, mixed, mesic Lamellic Hapludalfs), greenhouse potting mix (40:40:20 mixture of peat, perlite, lime; Michigan Grower Products, Galesburg, MI), and composted dairy manure (Dairy Doo®, Morgan's Composting, Sears, MI). Use of this mix in previous studies demonstrated sufficient nutrient supply from compost for vigorous plant growth. Seeds of each plant species were sown separately in 10 pots and thinned to 18 seedlings per pot at 6 to 10 DAS. Greenhouse temperatures were 27/19 C day/night for Run 1 and 22/18 C for Run 2. Plants were watered as needed to avoid drought stress.

Plant anchorage forces and heights were sampled six times at approximately 3-d intervals from 6 to 22 DAS. At each sampling date, 30 randomly selected individuals per species (3 per pot) were measured. The anchorage force of each plant was estimated by clamping the shoot with a plastic ridged "tarp clip" (Outus Crocodile Mouth Tarp Clips-004, $9 \times 3 \times 2$ cm) and pulling slowly upward using a force gauge (Alluris FMI-S30, Freiburg, Germany) to measure the force required to uproot.

Because greenhouse temperatures were different between the two runs, we combined data using growing degree days. Cumulative growing degree days to measurement date d were calculated:

$$GDD = \sum_{t=1}^{d} \frac{(T_{max} - T_{min})}{2} - 5 \quad (13)$$

where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature, and 5 C is the base temperature.

Mean height and anchorage forces for the two runs were combined for sampling dates in cases where the growing degree day units were similar (±5 GDD), resulting in anchorage force and height datasets for each species from 30 to 60 individuals for each of the six timings included in the simulations.

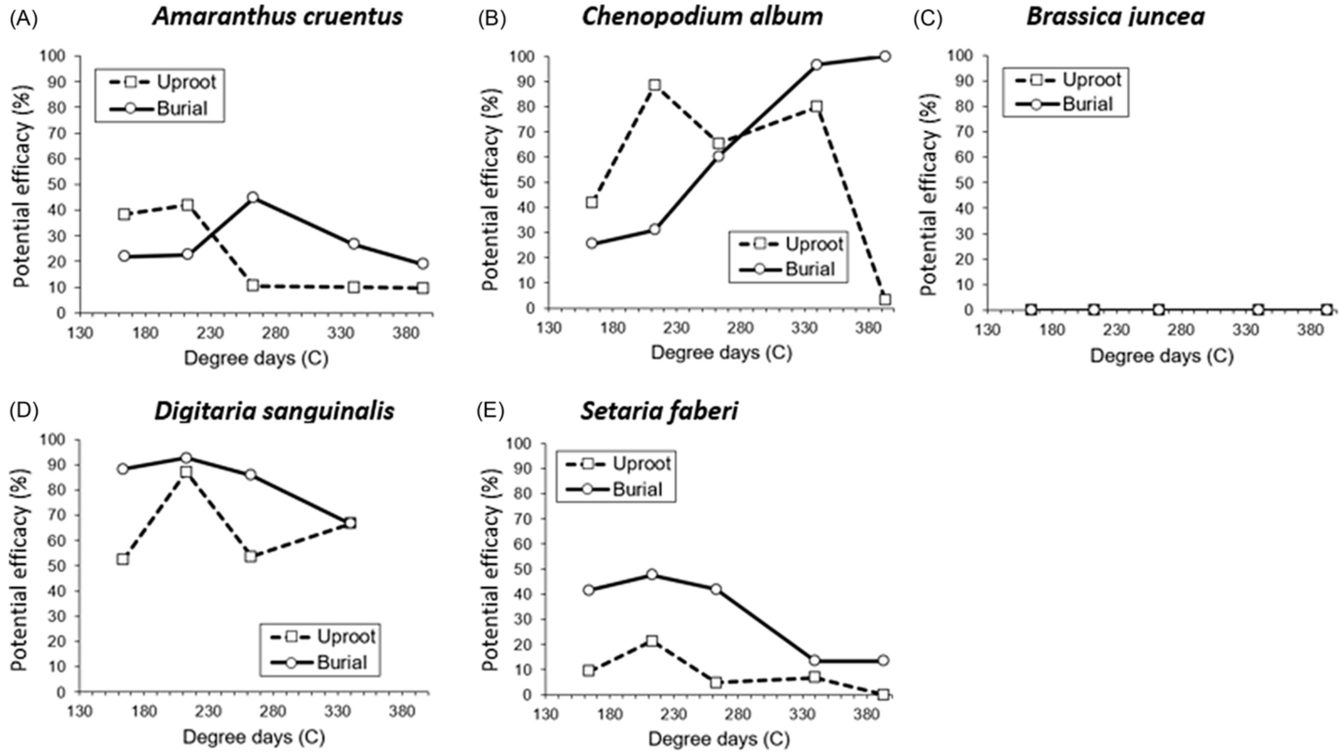

Figure 2. Baseline model predictions of potential efficacy (PE) of uprooting or burial at 160–350 growing degree days (GDD; baseline = 5 C; approximately 10–23 d at 20 C) after planting for (A) *Amaranthus cruentus*, (B) *Chenopodium album*, (C) *Brassica juncea*, (D) *Digitaria sanguinalis*, and (E) *Setaria faberi*. Modeled PE is calculated assuming 5% crop mortality (see "Materials and Methods" for additional model details). Data in model collected in greenhouse trials in East Lansing, MI, in 2021.

Results and Discussion

Illustration of Modeling Procedure

Our simulation approach is illustrated in Figure 1, which shows anchorage force and height data for 60 individual carrot and 60 *C. album* seedlings sampled at 263 GDD after planting. In this case the uprooting force (F^*) that would kill 5% of the carrots is equivalent to the third lowest carrot anchorage force (see Equation 5; $a = 0.05 \times 60 = 3$), or 0.31 N, and the threshold burial height (H^*) is equivalent to the third shortest carrot height or 2.9 cm (Equation 6). The three individual carrots (5% of total) that would die from uprooting are indicated in blue and green, and those that would die from burial are indicated in yellow and green. Note that in this case, one individual carrot (indicated in green) would die from either uprooting at F^* or burial at H^*. Then, we estimated PE_U and PE_B for *C. album* by calculating the percentage of individuals with anchorage forces less than F^*, or heights less than H^*, respectively (Equations 7 to 10). In this case, application of the threshold uprooting force F^* that limits carrot mortality to 5% (0.31 N from Figure 1A) would result in uprooting of 45 individual *C. album* seedlings (indicated in blue and green in Figure 1B). Similarly, application of burial depth H^* that limits carrot mortality to 5% (2.9 cm from Figure 1A), would result in burial of 38 individual *C. album* seedings (indicated in yellow and green). In this example, PE_U would therefore be 70% (= 42/60), and PE_B would be 68% (= 41/60).

Baseline Simulation Predictions

PE of Burial and Uprooting Varies with Species and Timing

Under our baseline simulation assumptions, we found that—as expected—PE varies considerably with weed species, plant age, and tool mechanism of action (Figure 2). For the broadleaf species *A. cruentus* (Figure 2A) and *C. album* (Figure 2B), PE is initially higher for uprooting than burial, but the PE of burial increases over time, exceeding that of uprooting after 263 GDD. In contrast, for both grass species, PE from burial is higher than from uprooting over the entire period (Figure 2D and 2E). For *B. juncea* (Figure 2C), the PE of both tools is zero; in other words, our simulation predicts that it is not possible to kill *B. juncea* with tools that uproot or bury without also killing at least 5% of the carrot crop.

Interestingly, for three of the five weed species included in our simulations, PE is predicted to be highest when tools are applied between 164 and 263 GDD (approximately 1 to 2 wk) from planting (Figure 2). For those species, delaying cultivation beyond that point results in lower efficacy, as weeds gain a relative advantage in both height and anchorage force. For *C. album*, predicted PE follows a different pattern, with maximum PE for both uprooting and burial occurring at 213 GDD or later, and increases in PE for burial occurring up to at least 393 GDD (approximately 3 wk) from planting (Figure 2B). These results demonstrate that the optimal tool choice and timing for cultivating carrots is likely to vary with weed community composition. In situations where annual grass species like *D. sanguinalis* and *S. faberi* dominate, cultivation between 164 and 263 GDD (1 to 2 wk) after planting with tools that bury is predicted to provide the best results (50% to 90% weed mortality with 5% mortality of carrots; Figure 2D and 2E). In contrast, fields dominated by broadleaf weeds like *C. album* or *A. cruentus* might be best controlled with tools that uproot at early growth stages (1 to 2 wk after planting) and tools that hill at later growth stages.

These results also demonstrate the inherent challenge of successfully cultivating a slow- growing, sensitive vegetable crop

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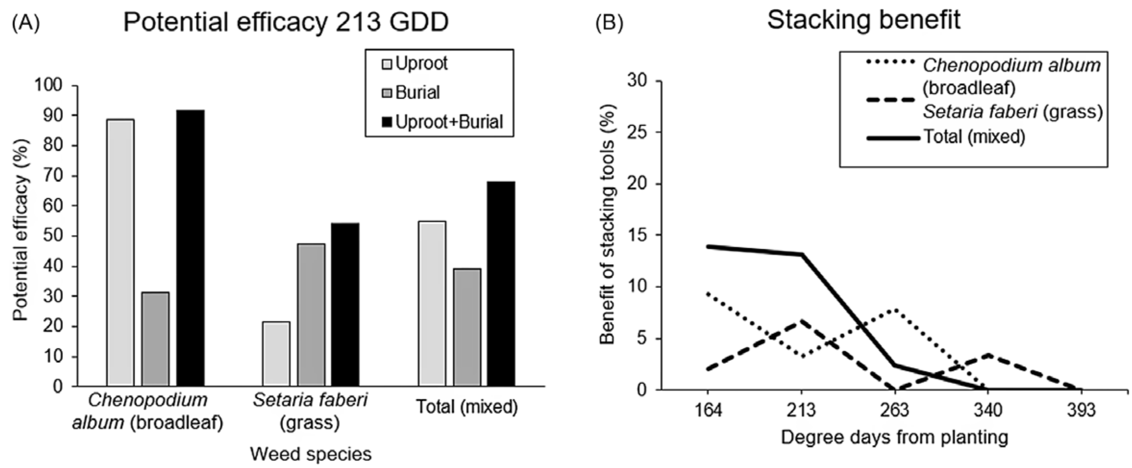

Figure 3. Modeled impacts of tool stacking on (A) predicted potential efficacy (PE) of uprooting, burial, or their combination on broadleaf, grass, and mixed weed communities at 213 growing degree days (GDD); (b) predicted benefit of stacking, $[PE_S - \max(PE_U, PE_B)]$, over time for broadleaf, grass, and mixed weed communities. PE is estimated assuming 5% crop mortality (see "Materials and Methods" for additional assumptions).

like carrots. When weed species like *A. cruentus*, *B. juncea*, or *S. faberi* are present, maximum PE is less than 50% under our baseline assumptions (Figure 2A, C, and E). In subsequent simulations, we explore potential improvements in PE resulting from cultural practices used with mechanical cultivation.

Simulated Impacts of Tool Stacking

Tool Stacking Improves PE in Mixed Grass–Broadleaf Weed Communities

One suggested approach for improving efficacy and selectivity of mechanical cultivation involves combining tools with different mechanisms of action, or tool stacking (Gallandt et al. 2018), although empirical tests of this approach have shown mixed results (Brown and Gallandt 2018; Tilton 2018). Our simulation illustrates conditions under which such tool stacking is likely to increase the PE of cultivation, as well as conditions under which it may have minimal effect. At 213 GDD, our simulation predicts that stacking tools that uproot with those that subsequently bury would have little impact on PE for control of *C. album* or *S. faberi* compared with the use of a single optimal mechanism of action (Figure 3A). However, for a mixed community of these two species, our simulation predicts that the additive effects of stacking would increase PE by approximately 28% compared with burial alone. These results support the idea that diverse weed communities are more successfully managed with diverse mechanisms of action.

The simulation also illustrates how the benefits of stacking may change over time during crop development (Figure 3B). For example, the predicted benefit of stacking tools in a carrot crop with an evenly mixed community of *C. album* and *S. faberi* is greatest at 164 GDD and declines thereafter. This result reflects the fact that over time, *C. album* becomes more susceptible to burial compared with uprooting (Figure 2), and suggests that once carrots are well established, carrot growers may benefit from focusing their attention on adjusting burial tools to hill with precision, rather than stacking tools with multiple mechanisms of action.

Effects of Cultural Practices on PE of Cultivation

Stale Seedbedding Greatly Improves PE in Most Cases

When we adjust our model to simulate the effects of stale seedbedding, PE increases for both tool mechanisms of action in almost all cases (Figure 4). For example, at 263 GDD from carrot seeding, the predicted PE of uprooting for *A. cruentus* increases from 10% (Figure 4A; solid line) to greater than 80% when stale seedbedding is used (Figure 4B; solid line). Similarly, when stale seedbedding is combined with tools that bury, the PE of burial increases to 100% for all species other than *B. juncea* (Figure 4D; solid line). For *B. juncea*, stale seedbedding in combination with burial results in an increase in PE from 0% (Figure 4C) to greater than 50% (Figure 4D).

Stale seedbedding is typically cited as an important tool for depleting the weed seedbank in the shallow soil profile, thereby reducing the *density* of weeds emerging with crops (e.g., Boyd et al. 2006; Riemens et al. 2007). However, our results demonstrate the impact of stale seedbedding on the *size* of weeds at the time of cultivation; by delaying emergence of weeds relative to the crop, stale seedbedding effectively reduces either the height or anchorage force of weeds relative to the crop, thereby facilitating improved selectivity.

Vigorous Crop Cultivars and High-Quality Seed Improve PE

Our simulation also illustrates the extent to which cultural practices that increase crop height or anchorage force relative to weeds can increase the PE of mechanical cultivation (Figure 4). For example, previous research demonstrates that the use of larger seed-size fractions of commercial seeds of Bolero carrots results in seedlings with approximately 20% greater anchorage force and 12% greater height at 2 wk after planting compared with those from smaller seed-size fractions (Connors 2022; Tilton 2018). Results from our simulations suggest that such increases in carrot seed vigor would correspond to improvements in PE of 5% to 20% depending on weed species (Figure 4A and 4C, Example 1). When integrated with stale seedbedding, our simulations demonstrate that use of vigorous carrot seed lots could facilitate acceptable levels of control of even the most challenging weed species (e.g., *B. juncea*; Figure 4D, Example 1).

Our simulation also illustrates the importance of using vigorous cultivars to improve the PE of mechanical cultivation tools. For example, in our best-case scenario for cultivation tool success of *B. juncea*—hilling following stale seedbedding—predicted PE drops from around 50% for our baseline carrot cultivar (Bolero) to less than 20% for less vigorous carrot cultivars like Danvers or Napoli

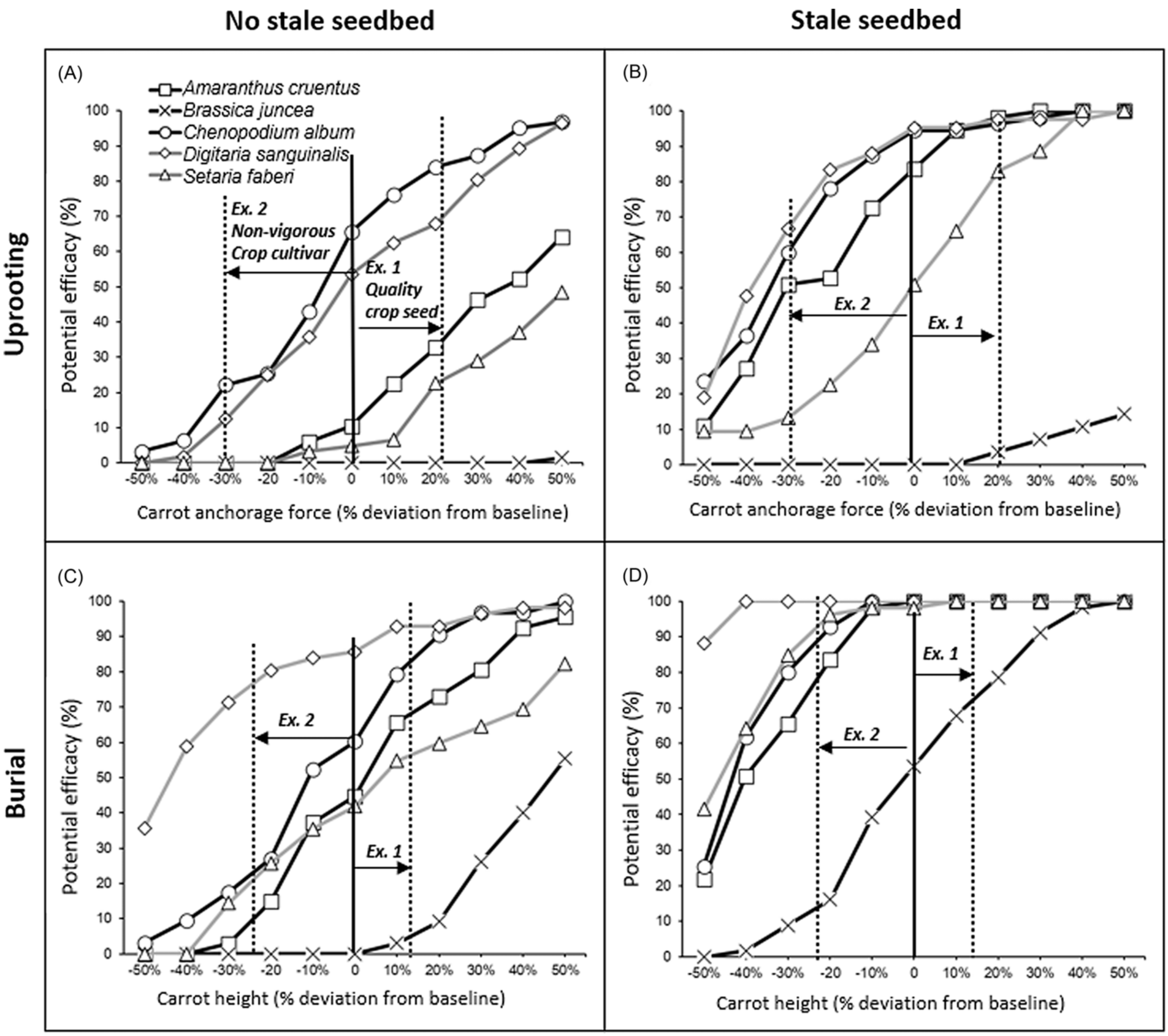

Figure 4. Simulated impacts of cultural practices on potential efficacy (PE) of mechanical cultivation. Predicted PE of uprooting (A and B) or burial (C and D) on five plant species in the absence of stale seedbedding (A and C) or with stale seedbedding (B and D), under varying assumptions regarding carrot anchorage force and height. Mean carrot height and anchorage force used in our baseline model are indicated with a solid line in each figure. Examples of cultural practices that alter carrot height or anchorage forces are illustrated in Examples 1 (use of vigorous crop seed lots) and 2 (use of non-vigorous crop cultivars). PE is estimated assuming 5% crop mortality (see "Materials and Methods" for additional assumptions).

(Figure 4D, Example 2), based on data from Tilton (2018). Conversely, use of more vigorous cultivars like those described by Colquhoun et al. (2017) may improve the PE of mechanical cultivation, while simultaneously improving crop competitiveness against escaped weeds.

Conclusions and Future Directions

Although our simulations provide useful insights into the optimal type and timing of mechanical cultivation for specific crop–weed combinations, results must be viewed within the context of the assumptions. First, our baseline model was parameterized using height and anchorage force datasets from greenhouse-grown plants (Table 1) that may deviate from field-grown plants depending on environmental conditions. Our estimates of anchorage forces from greenhouse grown plants are similar to those reported for carrots (Fogelberg and Dock Gustavsson 1998) and various weed species (Asaf et al. 2024; Fogelberg and Dock Gustavsson 1998), but differ substantially from those reported by Toukura et al. (2006) at some growth stages. This may be due to weeds' known plastic responses to light quality and quantity (Aphalo et al. 1999; Brainard et al. 2005; Morgan and Smith 1978), or to soil effects on root anchorage development (Ennos 2000; Fogelberg and Dock Gustavsson 1998). To improve our simulations, more datasets are needed that simultaneously characterize height and anchorage force distributions of both crops and weeds over time under typical field conditions.

Second, our model is based on various simplifying assumptions regarding crop and weed sensitivity to burial and uprooting. For example, we assume that weeds or crops die if and only if they are completely buried. In reality, as Mohler et al. (2016) demonstrated, a small fraction of seedlings of some weed species can recover from complete burial, and others may die even if only partially buried. Equally important from a practical perspective are potential negative impacts of partial uprooting or burial on crop quality and yield. More empirical evaluation of cultivation tool impacts on the quality and yield of specific crops (independent of weed competition and crop death) are needed to improve model performance.

In interpreting our results, it is important to keep in mind that the model only provides an estimate of the *potential* efficacy of idealized tools with optimized settings. Under field conditions, *actual* tools rarely apply a uniform uprooting force or consistent burial depths, and settings are rarely calibrated perfectly to achieve predicted selective potential (Kurstjens et al. 2004). Tools apply variable uprooting forces and burial depths depending on the location of the tool compared to the plant, soil conditions at the time of cultivation, and tool settings (Connors 2022; Gallandt et al. 2018; Mohler et al. 2016; Parks and Gallandt 2023; Terpstra and Kouwenhoven 1981).

Overall, despite these caveats, our model provides a powerful tool for understanding mechanisms underlying selectivity of mechanical cultivation tools. In the specific context of carrots, our results illustrate the critical importance of integrating cultural practices (e.g., stale seedbedding and cultivar choice) that enhance the size differential between carrots and associated weeds before application of any mechanical tools. Our results suggest that for carrots, attaining differences in height (e.g., use of cultivars and practices that ensure rapid shoot growth), is likely to have greater payoff for improving selectivity than attaining differences in anchorage force, because the PE of burial is generally higher than that of uprooting. Our model also sheds light on the potential benefits and limitations of tool stacking. We demonstrate that tool stacking is likely to be most beneficial in the presence of diverse grass–broadleaf weed communities. However, in the case of carrots, potential benefits of stacking are shown to be relatively small and decline over time, as the susceptibility of all weeds to burial relative to uprooting increases.

Beyond its specific application in carrots, our model illustrates a relatively simple generalizable method for predicting the optimal mechanism of action (burial vs. uprooting) and timing for mechanical cultivation for any weed–crop combination given height and anchorage force datasets. It also allows exploration of the potential benefits of integrating cultural practices that effectively increase the height or anchorage force of crops relative to weeds at the time of mechanical cultivation. As such, the model provides a useful tool for generating hypotheses to facilitate efficient identification of potentially effective approaches for selective weed control across a range of cropping systems.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2025.10047

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