Effects of crop rotation on common waterhemp population dynamics: prospective and retrospective analyses

# Abstract

Crop bio-physiological characteristics and management requirements can affect weed populations’ dynamics differently. One way to examine such differences is to track changes in common waterhemp populations concerning the applied crop management using periodic matrices. We used a chain of six periodic matrices in each of nine crop environments crossed with two corn weed management regimes to project population trajectories in two scenarios of plant fecundity, representing two levels of control efficacy (high and low). Each crop environment identifies a crop species (corn, soybean, oat, or alfalfa) in a rotation (2-year, 3-year, or 4-year). Only corn and soybean received chemical herbicide. Both literature and empirically measured data were used. The crop sequences in the 2-year, 3-year, and 4-year rotations are corn - soybean; corn - soybean - oat intercropped with red clover; and corn - soybean - oat intercropped with alfalfa - alfalfa. Under the high control efficacy scenario, five waterhemp population sizes declined at the annualized rate of to , but the waterhemp population size in the 4-year rotation with low herbicide corn weed management slightly increased (). Under the low control efficacy scenario, waterhemp population sizes increased the fastest in the 2-year rotation ( to ) and the slowest in the 4-year rotation ( to ). The slower rates of population growth in the more diverse rotation were attributed to declining in the oat, red clover, and alfalfa crop environments that are cool-season crops. In addition to population projection, we examined the seed production and mature plant density thresholds in the three rotations for stabilizing population size using the inputs from the low-efficacy scenario. The difference in seed production and mature plant density thresholds was more pronounced between the 2-year and 4-year rotations than any other pairwise comparison.

# Introduction

In arable land, a low-density weed seedbank is highly desired. A weed species’ seedbank persistence is often influenced by multiple factors, including burial depth, tillage regime, and crop environment (Steckel et al., 2007). Common waterhemp (*Amaranthus tuberculatus* (Moq.) J.D. Sauer) is an agronomically challenging weed species (Johnson et al., 2009; Prince et al., 2012) whose high fecundity, high relative growth rate (Heneghan and Johnson, 2017), rapid herbicide resistance development (Tranel, 2021), and extended emergence pattern (Buhler and Hartzler, 2001) can help maintain an abundant seedbank (Davis, 2008; Korres et al., 2018).

To increase labor use efficiency in waterhemp management and to better regulate the weed’s population dynamics, it is helpful to know possible choke points throughout the weed’s life cycle, where intervention can substantially reduce the population growth rate. Following the population in complete life cycles in different crop environments can help identify the choke points where management could be focused (Caswell, 2001). Combining demographic parameters from multiple sources and organizing them in different scenarios can facilitate the evaluation of population responses without extensive field measurement (Caswell, 2001; Davis, 2002; Ullrich, 2000). In addition, retrospective perturbation analysis can be used to examine how a population would change if changes occurred at different points throughout the species’ life cycle (Caswell, 2001; Davis, 2002; Ullrich, 2000).

Interseeding red clover (*Trifolium pratense* L.) with wheat (*Triticum aestivum* L.) followed by spring tillage delayed and reduced giant foxtail (*Setaria faberi* Herrm ) seedling emergence as compared with three other interseeding and tillage timing combinations (Davis and Liebman, 2003). Cool-season crops, such as oat (*Avena sativa* L.), red clover, and alfalfa (*Medicago sativa* L.), can be planted in early spring or the fall and overwinter to limit waterhemp’s exposure to sunlight at the time of its emergence. Our search of the current literature did not return any information on waterhemp’s population dynamics in other cool-season crops, so we measured the following characteristics of waterhemp in cool-season crop environments: plant fecundity (Nguyen and Liebman, 2022a), soil seedbank density, the timing of seedling emergence and resultant densities, and plant survival (from seedling to mature).

Extending a conventional 2-year rotation of corn and soybean to contain oat, red clover, and alfalfa effectively maintained a weed community at an abundance level that did not coincide with a reduction in crop yields (Nguyen and Liebman, 2022b). Even though waterhemp’s reproductive potentials could be reduced without heavy reliance on herbicides (Nguyen and Liebman, 2022a), the effects of cropping system diversification on common waterhemp abundance were not clearly defined (Nguyen and Liebman, 2022b). A heuristic model for waterhemp population dynamics in corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) (two warm-season annual crops) with or without a rye (*Secale cereale* L.) cover crop (a cool-season species) in between the corn and soybean phases indicated that the cover crop would provide minimal suppression of waterhemp population densities. To explore other options for regulating waterhemp population dynamics, we conducted a prospective analysis using a population matrix approach (Caswell, 2001; Davis, 2002; Ullrich, 2000).

We employed a periodic matrix model (Caswell, 2001; Cousens and Mortimer, 1995) to examine the effects of various events, i.e., crop management activities, that occur throughout the life cycle of waterhemp on the population change rates, . We used the general equation of (Caswell, 2001) to study from one period to another. The waterhemp populations in our study were depth-structured for the soil seedbank and cohort-structured for plants. The structure of the population helps accommodate different seed survival rates (Buhler and Hartzler, 2001; Yenish et al., 1992) and seedling emergence rates (Werle et al., 2014) from different depths, plant survival rates, plant size, and fecundity of different cohorts (Hartzler et al., 2004; Nordby and Hartzler, 2004).

In addition, we simulated how a waterhemp population could be kept from increasing () by manipulating seed production (seeds m-2) and mature plant density (plants m-2) to establish two sets of thresholds. We chose simulation over a life-table response experiment (LTRE) approach because we were interested in how the seedbank population changes in each crop rotation and because the available data set used in the projection exercise was different in only one sub-annual period: seed production. LTRE would be more appropriate if there were more varying sub-annual periods.

The modeling approach here combined demographic parameters from the literature and empirical data from our fieldwork. We hypothesized that extending a conventional 2-year rotation of corn and soybean with the cool-season crops oat, red clover, and alfalfa could accelerate the depletion of waterhemp seedbanks in the soil.

# Materials and methods

### Experiment design

To study how common waterhemp’s demography differs in three cropping systems suitable for the Midwestern USA, we used a factorial experiment design with nine crop identities crossed with two weed management regimes. Crop identity was assigned to main plots and comprised the combination of crop species and rotation system. The different weed management regimes were assigned to split plots and comprised conventional versus low herbicide regimes applied to the corn phase of each of the three rotation systems. The rotation systems used in this study comprised a 2-year corn-soybean rotation, a 3-year corn - soybean - oat (*Avena sativa* L.) intercropped with red clover (*Trifolium pratense* L.) rotation, and a 4-year corn - soybean - oat intercropped with alfalfa (*Medicago sativa* L.) - alfalfa rotation. There were four replications of each crop identity x herbicide regime combination. Field plots were located at the Iowa State University Agricultural Engineering and Agronomy Research Farm in Boone County, Iowa, USA.

The general experiment design was provided by Nguyen and Liebman (2022a), but a more explicit description, including tillage regimes used for each treatment, is shown in Figure 1. Contrasting herbicide regimes were used for corn at the experiment site from 2008 through 2020; soybean plots in the contrasting weed management regimes were treated with different herbicides during the 2008-2016 period but with the same herbicide regime during 2017-2020. During the present study, data were collected in each experimental unit (eu) to accommodate the different weed management programs used in the corn phase of all crop rotations.

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*Figure 1: Conceptual diagram of the three rotation systems compared within the experiment. A cycle of four calendar years is shown. Tillage regimes are symbolized with arrows: thin, black ahead of crop sowing for field cultivation and medium, blue and bold orange after crop harvest for chisel and moldboard plowing, respectively. Crops are color-coded and displayed for the approximate months they were in the field. The emergence and establishment of common waterhemp plants are illustrated with black symbols. Grey plants shown in oat or alfalfa’s first year were physically controlled by crop harvest operations. Grey plants shown in alfalfa’s second year were physically suppressed three to four times by hay harvest. Alfalfa hay was harvested when approximately 15% of the plants flowered. Red clover in the O3 treatment and alfalfa in the A4 treatment were terminated by plowing in the late fall before growing corn in the following year, so the dark green bar in the 3-year rotation represents volunteer red clover, and the light green bar in the 4-year rotation represents the living alfalfa residue in the C4 treatment.*

### Data collection and analysis

The demographic information presented here is only for female waterhemp seeds and plants because 1) waterhemp is a dioecious species with a roughly 1 : 1 sex ratio (Costea et al., 2005; Montgomery et al., 2021; Montgomery et al., 2019); 2) only female individuals bear seeds (Costea et al., 2005); and 3) pollen grains are abundantly available during reproduction (Liu et al., 2012). All plant characteristics were reported for each cohort, and seedbank densities were reported for two soil strata: 0 - 2 cm and 2 - 20 cm.

#### Seed densities and seed fates in the soil seedbank

Nine groups of four 20-cm deep soil cores arranged in a 3 x 3 grid were collected in the fall of 2019 from each experimental unit (eu). Each soil core was cut into two sections, the top 2 cm and the bottom 18 cm. No deeper sampling was collected because the tillage regimes applied at the experiment affected the top 0 - 20 cm of the soil. All the 0 – 2 cm sections in each eu were packed separately from all the 2 – 20 cm sections, so each eu yielded two data points, one for each of the two soil strata. Seeds were separated from the soil materials and plant residues using elutriation and flotation (Forcella et al., 2003). Clean seeds were placed on germination paper imbibed with distilled water in Petri dishes and incubated in 28/18 degree Celsius light/dark - 18/8 hour night/day conditions for five days. Proportions of dormant, readily germinable, and dead seeds were classified as follows: germinated as readily germinable; firm and unyielding to forceps pressure as dormant; and yielding to forceps pressure as dead (Borza et al., 2007). Readily germinable and dormant seeds were grouped as viable and used to calculate the emergence proportion (details on how the 2019 fall soil seedbank sample was used with data for 2020 seedling emergence to determine the emergence proportion are provided in Appendix B – Matrix assembly).

#### Seedling emergence pattern and timing

In the 2019 field season, non-destructive emergence surveys were conducted once every two to three weeks (weather permitting) in eight quadrats per eu. Seedlings were marked with color-coded toothpicks for cohort identification. Within an eu, seedlings in the same cohort were marked with the same toothpick color. Six cohorts of plants were followed from seedling to senescence.

In the 2020 field season, destructive emergence surveys were conducted in eight quadrats per eu. Seedlings were clipped at the base of the plant without disturbing the soil. With the intention of evaluating the proportion of seed germinated from the top 2 cm layer of the soil, eight to ten cohorts (depending on the crop environments) were recorded, but only the first six cohorts were included in Scenario 1 for consistency.

The number of seedlings in each cohort was converted to population density (seedlings m). The empirically estimated emergence rates () were deemed too different from the results of Schutte and Davis (2014) and Buhler and Hartzler (2001) so we adjusted the estimation to reflect higher emergence rates based on a 20% germination rate (Appendix B – Matrix assembly). We used a 20% emergence rate following Schutte and Davis (2014)’s results because their investigation comprised 129 waterhemp populations. The date of first emergence detection in a crop identity was noted as the date that cohort 1 emerged in that crop identity.

#### Statistical analysis of the measured parameters

All the response variables were analyzed with factorial mixed-effect models, in which crop identity (crop species in each rotation) was the main-plot effect, corn weed management was the split-plot effect, and cohort identity was the covariance. The response variables were transformed as needed to correct heteroscedasticity.  
For the emergence timing evaluation, a factorial model with crop species, instead of crop identity, being the main-plot factor and corn weed management being the split-plot factor, was fitted on Julian dates of the first emergence because of small sample sizes in cohorts 2 and beyond. We feel that a slight modification of the statistical model was acceptable because we were interested in the difference in waterhemp emergence in different crop environments.

### Model assumptions

The assumptions used in the modeling exercise in this manuscript are listed in Table 1.

Table 1: Female-only population dynamics model assumptions for common waterhemp (Amaranthus tuberculatus)

| Stage | Assumption | References or justification |
| --- | --- | --- |
| All | Sex is stable throughout the life cycle | Montgomery et al., 2019 and 2021 |
|  | Equal growth rate across individuals of the same size and shape under the same treatments (crop x rotation x herbicide regime) | Chapter 8, Caswell, 2001 |
| Seed | Equal germination probability across sexes | No evidence of sexually differentiated seed germination probability |
|  | The sex ratio is 1:1 | Costea et al., 2005 |
|  | Sex is determined at seed formation | Montgomery et al., 2019 and 2021 |
|  | Seedlings only emerge from the 0 - 2 cm soil stratum | No estimation for waterhemp in the same field settings as ours were available, so we used the estimation for redroot pigweed (*A. retroflexus*), a closely related species, following Mohler and Galford, 2008 |
|  | Germination is fatal in the 2 - 20 cm soil stratum | Davis and Renner, 2007 |
|  | 100 % of the germinated seeds from the 0 – 2 cm soil stratum in the post-emergence herbicide treated eu successfully emerged | Assumed for simplicity of the model. The seedling emergence were surveyed approximately every two weeks so emergence was promptly recorded before seedlings were affected by existing mortality factors. |
|  | 5 % of the germinated seeds from the 0 – 2 cm soil stratum in the pre-emergence herbicide treated eu (Thiencarbazone-methyl and isoxaflutole mixture and mesotrione) successfully emerged | Thiencarbazone-methyl and isoxaflutole mixture and mesotrione are 97.5% and 70.75% efficacious against other *Amaranthus* species (Sutton et al., 2002 and Janak and Grichar, 2016) |
|  | 50% of the germinated seeds from the 0 – 2 cm soil stratum in the eu that were not treated with herbicides successfully emerged | Assumed for the simplicity of the model and for illustrating that pre-emergence herbicides are more potent than allelochemicals on seed germination inhibition.  Red clover allelopathic chemical can inhibit up to 40% germination and up to 70% radicle length (Liebman and Sundberg, 2006), oat can promote weed germination (Cornellius and Bradley, 2017), and alfalfa extract can inhibit both seed germination and radicle elongation (Chung and Miller, 2005). |
|  | Equal decay rate across sexes | No evidence of sexually differentiated seed decay rate |
|  | Different decay rates for burial depths | Buhler et al., 2001, Steckel et al., 2007; Mohler and Galford, 2008; and Sosnoskie et al., 2013 |
|  | Equal palatability to granivores across sexes | No evidence of sexually differentiated palatability |
|  | Granivore activities are an important threat | van der Laat et al., 2015 |
| Young plant | Female plants are more likely to survive under stressful conditions than male plants | Deduced collectively from the general 1:1 sex ratio (Costea et al. 2005) and differentiated sex ratio at maturity across weed management systems at the experiment site in 2018 (Nguyen and Liebman 2022b) |
|  | Competition with crops for resources is expressed in multiple periods | Specific mortality or size reduction caused by crops was not measured |
|  | Competition with other weed species is excluded | Excluded for simplicity of the model |
|  | Intraspecific competition is included in the survival rate from seedling through maturity | Specific mortality or size reduction caused by other weed species was not measured |
|  | The weed control program tailored to the specific crop is the main cause of mortality | Ryan et al., 2010 |
| Mature plant | Pollen is abundantly available to all female plants at the reproductive stage | Pollen grains can remain viable for five days after dispersal (Liu et al., 2012), and the populations at the experiment site were close to sexual parity with abundant plant densities (Nguyen and Liebman, 2022b) |
|  | 50% of the seeds produced by each female plant are female | Costea et al., 2005 |
|  | The male:female ratio can deviate from the 1:1 ratio under different conditions | Nguyen and Liebman 2022b and Montgomery et al., 2019 and 2021 |

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### Matrix form

Each rotation transition matrix () is the product of two, three, or four annual projection matrices, (r = 2, 3, or 4, corresponding to the number of crop phases in each rotation, and w = conventional (conv) or low, corresponding to the weed management regime applied in the corn phase). Each set of annual projection matrices, corresponding to a crop environment, , is the product of six sub-annual matrices, with . The six sub-annual matrices, in chronological order from spring to winter, are pre-planting tillage-induced seed vertical movement (), emergence (), summer seed and seedling survival (), fecundity (), post-harvest tillage induced vertical seed movement (), and overwinter seed survival ().

Any transition matrix (periodic sub-annual (), annual (), or rotational ()), is of eight rows by eight columns (8 x 8) and consists of four blocks using the format of matrix 4.8 in Chapter 4 of Caswell (2001).

where,  
, 2 x 2, is the transition within the seedbank population (tillage-induced seed movement and summer and overwinter seed survival),  
, 6 x 6, is the transition within the plant population (seedling survival to maturity),  
, 6 x 2, is the transition from the seedbank to the plant population (emergence), and  
, 2 x 6, is the transition from the plant to the seedbank population (distribution of newly produced seeds to the soil seedbank).

The compilation of each matrix, from the published literature, empirical measurement, or both sources of parameters is detailed in the *Parameterization* section. In total, eighteen sets of six sub-annual periodic matrices were used. Each set of sub-annual matrices was constructed for every crop identity crossed with corn weed management combination. Population transition matrices were calculated using Wood’s quadratic programming method (Section 6.2, Caswell, 2001).

### Parameterization

Waterhemp plant size is highly variable; consequently, individual plant fecundity is highly variable. For example, the biomass of the smallest recorded waterhemp in our experiment was < 0.001 g, whereas the dried weight of the largest plant was about 1 kg (data not shown). The control efficacy of the weed management programs on waterhemp is, therefore, more informatively reflected by fecundity (seeds/plant) or seed production (seeds m) than plant density.

To accommodate the elasticity of plant size and to examine the impact of different levels of control efficacy on population dynamics, two scenarios of control efficacy levels reflected by seed production are presented in this paper. The fecundity values for the two scenarios were assessed with different approaches (see *Plant fecundity* for details). In scenario 1, plant cohorts were recorded. In Scenario 2, plant cohorts were assigned by their size, assuming that plant size decreases as emergence is delayed (Table 1). All the population parameters were calculated for a female-only population because only female plants bear seeds. Consequently, the modeled population size reflected half of the population size in reality. How a whole population (with both sexes present) affects crop production can be examined using crop performance in different weed pressure levels. The seedbank densities of the whole population (male and female) from 2014 through 2019 are shown in Figure A2.

The lower-level demographic parameters are demographic parameters at each sub-annual period () filling elements at positions that describe seed and plant dynamics. From left to right, the eight columns of a matrix are named as s\_t, s\_b, pt\_co\_1, …, p\_co\_6. The columns s\_t and s\_b represent two strata of the soil seedbank: the top 0 – 2 cm and the bottom 2-20 cm. The columns p\_co\_1 through p\_co\_6 represent the plant cohorts 1 through 6. The same order is applied down eight rows of .

The examined lower-level demographic parameters can be grouped based on their impacts on preserving and producing new seeds, hereafter referred to as seed production, seed preservation, and neutral parameters. The seed preserving parameters are the probability of seeds not emerging (). The seed-producing parameters are the emergence probabilities (), the survival rates of seeds () and seedlings () during summer, the fecundity rate (), and the survival rate over winter (). Even though emergence reduces the seedbank, the number of seeds that are produced from an emerged seedling that succeeds until seed production is substantial, so emergence is considered positively impacting new seed production (Davis, 2008). The neutral parameters for both seed preservation and seed production are tillage-induced seed movement across soil strata at the pre-planting () and post-harvest ) periods. The tillage-induced seed vertical movement rates are considered neutral parameters because the seeds that are kept at or moved to the 0-2 cm soil layer can be exposed to emergence stimulants or granivores, while the seeds that are kept at or moved to the 2-20 cm soil layer can germinate without reaching the soil surface (fatal germination), are exposed to decaying stimuli; or preserved at optimal conditions (Burnside et al., 1996; Davis et al., 2005; Davis and Renner, 2007).

Details of how each matrix was formed are in the Appendix, but a summary of each parameter's range is provided below.

Table 2: Female-only population dynamics model parameters for common waterhemp (Amaranthus tuberculatus)

| Parameter | Denomination | Unit | Corn | Soybean | Oat | Alfalfa |
| --- | --- | --- | --- | --- | --- | --- |
| Seeds in the top soil stratum stay | t\_11,s or t\_11,f | seeds seeds-1 | pre-planting: 0.59;  post-harvest: 0.59 | pre-planting: 0.59;  post-harvest: 1 | pre-planting: 0.59; post-harvest: 0.02 - 1 | pre-planting: 1;  post-harvest: 0.02 |
| Seeds in the top soil stratum move to the bottom stratum | t\_12,s or t\_12,f | seeds seeds-1 | pre-planting: 0.15;  post-harvest: 0.1 | pre-planting: 0.15;  post-harvest: 0 | pre-planting: 0.15; post-harvest: 0 - 0.07 | pre-planting: 0;  post-harvest: 0.07 |
| Seeds in the bottom soil stratum move to the top stratum | t\_21,s or t\_21,f | seeds seeds-1 | pre-planting: 0.41;  post-harvest: 0.41 | pre-planting: 0.41;  post-harvest: 0 | pre-planting: 0.41; post-harvest: 0 - 0.98 | pre-planting: 0;  post-harvest: 0.98 |
| Seeds at the bottom soil stratum stay | t\_22,s or t\_22,f | seeds seeds-1 | pre-planting: 0.85;  post-harvest: 0.9 | pre-planting: 0.85;  post-harvest: 1 | pre-planting: 0.85; post-harvest: 0.93 - 1 | pre-planting: 1;  post-harvest: 0.93 |
| Seed dormant rate during the crop season | d | seeds seeds-1 | 0.8 | 0.8 | 0.8 | 0.8 |
| Successful emergence rate | e\_1 through e\_6 | plants seeds-1 | 0.01 – 0.2 | 0.01 | 0.1 | 0.1 |
| Plant survival rate | s\_1,p through s\_6,p | plants plants-1 | 0.01 - 0.84 | 0 - 0.89 | 0.1 - 0.9 | 0.1 - 0.5 |
| Seed survival rate | s\_11,s, s\_22,s, o\_11,s o\_22,s | seeds seeds-1 | summer: 0.66 - 0.74;  overwinter: 0.66 - 0.74 | summer: 0.66 - 0.74;  overwinter: 0.66 - 0.74 | summer: 0.66 - 0.74; overwinter: 0.66 - 0.74 | summer: 0.66 - 0.74;  overwinter: 0.66 - 0.74 |
| Plant fecundity | f\_1 through f\_6 | seeds plant-1 | Scenario 1: 1.0 - 3518.6;  scenario 2: 18.8 – 93672.3 | scenario 1: 0 - 35.5;  scenario 2: 1756.2 – 1249255.0 | scenario 1: 3.9 - 964.0;  scenario 2: 66.3-3696.6 | scenario 1: 0.64 - 11.8;  scenario 2: 0.5 – 460.3 |

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### Modeling

Within a year, the waterhemp population projection from the sub-annual period to was reflected by the changes in the number of seeds and plants and calculated as follows (Chapters 2, 3, and 4, Caswell, 2001).

where,  
 is the square transition matrix from time to time , and  
 is the population vector (in column matrix form) of eight rows and one column.  
Waterhemp population transition in one crop phase, from pre-planting tillage to winter seed dormancy, is calculated with

where,  
 is the index for the crop phase in a particular rotation,  
 is the Leslie population matrix (Leslie, 1945) in the crop phase corn weed management , and  
 is the population transition matrix during summer

The main factors that contribute to the success of the control practices used for waterhemp are tillage regime, herbicides, cultivation practice, and crop competitiveness. Among those four factors, crop competitiveness is reflected in waterhemp emergence proportion, mature plant size and fecundity. The mature plant size was not included in this study but it was used as the intermediate value to calculate fecundity.

Matrix calculation in this study was performed in R version 4.2.0 (R Development Core Team, 2022).

#### Population growth rate

We projected population growth rates under two scenarios of high and low control efficacy reflected via seed production. The high-efficacy scenario (Scenario 1) and the low-efficacy scenario (Scenarios 2) used different fecundity values in the seed production sub-annual period but the same vital rates in all other sub-annual periods. The eigen.analysis function in the popbio package version 2.7 (Stubben et al., 2020) was applied on the matrices , , and to obtain the population growth rate () in each crop phase crossed with the corn weed management regime during the full crop cycle.

The rotation-wise population growth rates (, ) were extracted from the $lambda element in the comprehensive output of eigen.analysis for each of , , and . The annualized population growth rates for each rotation crossed with corn weed management regime (, , and ) were obtained by taking the square root, cubic root, and fourth root of , , and .

#### Simulations

Since plant fecundity was the most influential parameter on population growth (as shown in the population projection) and waterhemp was more prolific in the warm-season crop environments than the cool-season crop environments (Nguyen and Liebman, 2022a), we followed up with a simulation of seed production and mature plant density threshold in corn and soybean. We used a theoretical plot of 1 m2 with 10000 seeds in the top 0 - 2 cm soil stratum and 0 seeds in the 2 - 20 cm soil stratum. We followed that theoretical plot in three rotations (2-year, 3-year, and 4-year) crossed with two corn weed management regimes (conventional and low herbicide), as we did with empirical data collection at our research site. We were interested in the following question: ***How much weed control efficacy is necessary to stabilize a waterhemp population ()?***

Waterhemp control efficacy in this study is indicated by seed production (seeds m) instead of plant density (plants m) because waterhemp individual plant size is highly variable.

In each seed production threshold simulation iteration, a randomized number of seeds was generated for cohorts 1 through 3 using function rlnorm(1, m, s), in which m is the mean fecundity on the natural logarithm scale and s is the standard deviation on the natural logarithm scale. m and s were obtained from the general relationship of ln(individual fecundity +1) against ln(individual aboveground mass + 0.005) (Nguyen and Liebman 2022a) that pooled all the 389 data points from the whole experiment. Twenty-four pairs of m and s were estimated (details are in Table A5 in Appendix C). Different pairs of m and s were tried in the simulation until the rotation of interest’s annualized (m = m\*). Six values of m\* were identified for each corn and soybean phase of the three rotations. All the population characteristics, except for plant fecundity of cohorts 1 through 3, were kept as in the prospective modeling exercise. We estimated the necessary control efficacy in the corn and soybean crop environments by simulating the seed production threshold for plant cohorts 1 through 3. We only manipulated the fecundity of cohorts 1 through 3 because 1) the first three cohorts are more likely exposed to herbicides or cultivation than the later cohorts; 2) the first three cohorts, especially cohorts 1 and 2, have higher survival rates than the later cohorts; and 3) in general, the earlier cohorts of higher reproductive potential than the later cohorts.

In each mature plant density threshold simulation iteration, the input survival rates of cohorts 1 through 3 in the summer survival sub-annual matrix () was reduced until annualized in each treatment. If improving the control efficacy for mature plants above 99.999% (equivalent to reducing survival rates of cohorts 1 through 3 below 0.001) would not stabilize the population size, the later cohorts’ survival rates were manipulated. If 99.999% control efficacy of all six cohorts in corn and soybean would not stabilize the population size, intervention in soybean’s subsequent crops (oat and alfalfa) was applied. All the other five sub-annual matrices were kept the same as in the population projection exercise. The final manipulated survival rates were used with the unmanipulated survival rates to calculate the cohort-based mature plant density and population-wise plant density.

# Results and discussion

All the multi-year variables failed Levene’s test for equal variance, so those data were analyzed by year.

## Waterhemp sub-annual demographic parameters from empirical measurement

### Seedling emergence pattern and timing

Within the same calendar year, cumulative whole-season and cohort-based seedling densities were lower in the warm-season crops (corn and soybean) than in the cool-season crops (oat, red clover, and alfalfa) (Figure 2). Seedling emergence was delayed in the cool-season crops compared to warm-season crops (Tables 3 and 4). Waterhemp emergence was delayed by two weeks to a month in the alfalfa crop environment compared to the corn and soybean environments. Waterhemp emergence was nine to sixteen days earlier in oat than in alfalfa.

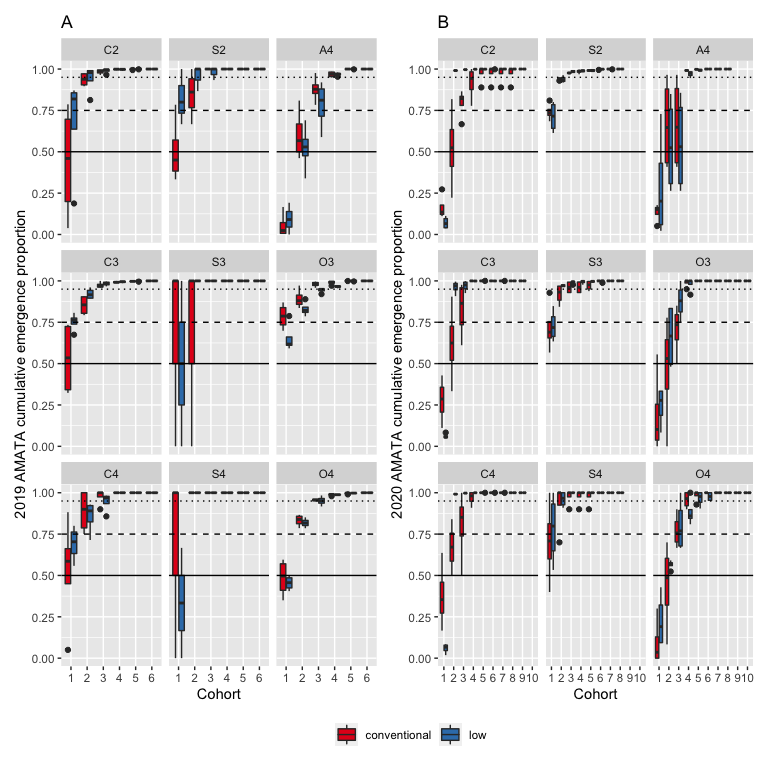


Figure 2: Data summary of cumulative emergence proportion of waterhemp in 2019 (A) and 2020 (B). The solid, dashed, and dotted lines indicate 50%, 75%, and 95% of total season emergence. The abbreviations on each section of panels A and B are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred (C2 - corn in the 2-year rotation, C3 - corn in the 3-year rotation, C4 - corn in the 4-year rotation, S2 - soybean in the 2-year rotation, S3 - soybean in the 3-year rotation, S4 - soybean in the 4-year rotation, O3 - oat in the 3-year rotation, O4 - oat in the 4-year rotation, and A4 - alfalfa in the 4-year rotation).

Table 3: 2019 and 2020 seedling emergence initiation in four crop environments (Julian date). Only the first seedling cohort was used as the response variable due to small sample sizes in the subsequent cohorts.

|  | 2019 | | | 2020 | | |
| --- | --- | --- | --- | --- | --- | --- |
| Crop | estimate | SE | df | estimate | SE | df |
| alfalfa | 154.0 | 1.3 | 61 | 163.0 | 0.1 | 61 |
| corn | 176.7 | 0.7 | 61 | 139.3 | 0.0 | 61 |
| oat | 150.0 | 0.9 | 61 | 141.0 | 0.1 | 61 |
| soybean | 189.0 | 0.7 | 61 | 163.0 | 0.0 | 61 |

Table 4: 2019 and 2020 seedling emergence timing (days) in four crop environments

|  | 2019 | | | | 2020 | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Contrast | difference | SE | df | p | difference | SE | df | p |
| alfalfa - corn | -22.7 | 1.5 | 61 | <.0001 | 23.8 | 0.1 | 61 | <.0001 |
| alfalfa - oat | 4.0 | 1.6 | 61 | 0.0596 | 22.0 | 0.1 | 61 | <.0001 |
| alfalfa - soybean | -35.0 | 1.5 | 61 | <.0001 | 0.0 | 0.1 | 61 | 1.0000 |
| corn - oat | 26.7 | 1.2 | 61 | <.0001 | -1.8 | 0.1 | 61 | <.0001 |
| corn - soybean | -12.3 | 1.0 | 61 | <.0001 | -23.8 | 0.1 | 61 | <.0001 |
| oat - soybean | -39.0 | 1.2 | 61 | <.0001 | -22.0 | 0.1 | 61 | <.0001 |

### 2019 soil seedbank and emergence proportion

In 2019, the waterhemp soil seedbank densities measured in the cool-season crop environments (O3, O4, and A4) in the fall after crop harvests were substantially higher than those of the warm-season crops. The waterhemp soil seedbank densities in the soybean environments were the lowest among all the crop environments (Table 5).

Table 5: 2019 seedbank densities (seeds/m2) at the top and bottom soil strata

|  |  |  |  | Top stratum density | | Bottom stratum density | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Rotation | Crop ID | Corn weed management | df | mean | SE | mean | SE |
| 2-year | C2 | conventional | 51 | 8,231.9 | 5,655.5 | 5,422.1 | 1,679.3 |
| 2-year | C2 | low | 51 | 4,811.6 | 3,306.0 | 3,938.9 | 1,220.0 |
| 2-year | S2 | conventional | 51 | 604.6 | 416.0 | 1,297.9 | 402.2 |
| 2-year | S2 | low | 51 | 1,451.2 | 997.6 | 1,612.6 | 499.6 |
| 3-year | C3 | conventional | 51 | 1,851.6 | 1,272.6 | 6,361.6 | 1,970.2 |
| 3-year | C3 | low | 51 | 1,781.0 | 1,224.1 | 8,922.5 | 2,763.2 |
| 3-year | S3 | conventional | 51 | 73.8 | 51.4 | 1,615.5 | 500.5 |
| 3-year | S3 | low | 51 | 303.6 | 209.2 | 1,831.5 | 567.5 |
| 3-year | O3 | conventional | 51 | 6,682.3 | 4,591.0 | 5,921.9 | 1,834.1 |
| 3-year | O3 | low | 51 | 8,513.1 | 5,848.7 | 5,292.1 | 1,639.1 |
| 4-year | C4 | conventional | 51 | 90.0 | 62.5 | 1,052.1 | 326.1 |
| 4-year | C4 | low | 51 | 77.9 | 54.2 | 1,300.8 | 403.1 |
| 4-year | S4 | conventional | 51 | 231.8 | 159.9 | 2,554.0 | 791.2 |
| 4-year | S4 | low | 51 | 375.6 | 258.7 | 3,717.3 | 1,151.4 |
| 4-year | O4 | conventional | 51 | 10,201.1 | 7,008.2 | 5,209.5 | 1,613.5 |
| 4-year | O4 | low | 51 | 13,770.2 | 9,460.0 | 4,590.4 | 1,421.8 |
| 4-year | A4 | conventional | 51 | 5,777.9 | 3,969.8 | 2,790.2 | 864.3 |
| 4-year | A4 | low | 51 | 8,022.3 | 5,511.5 | 3,415.9 | 1,058.1 |

## Waterhemp population growth rates

All the data sets for the empirically estimated sub-annual parameters were measured once. In 2019, individual plant size at maturity was measured for six cohorts in each quadrat of each eu, and two strata of soil seedbank were estimated between crop harvest and post-harvest tillage. In 2018, a different number of cohorts was followed in different crop environments because of limited labor availability and adverse weather conditions. The 2019 data were used for Scenario 1 because 2019 was the only year the soil seedbank samples were stratified (0 – 2 cm top stratum and 2 – 20 cm bottom stratum). Within the same rotation, a consistent pattern of top : bottom ratios of seed densities was observed between two corn weed management regimes. The seedbanks’ top : bottom partitioning after each crop phase differed between rotations and between crop identity of the same rotation.

### Scenario 1 – High control efficacy for seed production

In the high control efficacy, as reflected by the 2019 fecundity rates that were estimated from individual plant sizes using eighteen equations from Nguyen and Liebman (2022a), waterhemp population densities were projected to decrease ( ‹ 1.0) in all treatments, except in the 4-year rotation with low herbicide corn weed management (). Waterhemp populations were projected to decrease quickly in the 3-year and 4-year rotations under conventional herbicide corn weed management (Figure 3).

The top and bottom soil strata were evenly populated after the corn phase in all rotations crossed with corn weed management treatments, but a smaller portion of the seedbank was in the top soil stratum than in the bottom soil stratum in the soybean phase of all the rotations crossed with corn weed management treatments, and in the alfalfa phase of the 4-year rotation regardless of the corn weed management regimes. The top soil stratum was less populated than the bottom soil stratum after O3 but more populated than the bottom after O4.

Except for the 4-year rotation in which corn was treated with low herbicide weed management, all the other treatments’ decline of the waterhemp populations was attributed to the steady decrease of population size in the crop phases after corn. Even though the 2-year and 3-year rotations were of similar annualized population growth rates (, , , and ), a larger proportion of the seedbank was in the bottom soil stratum in the 3-year rotation, which can shrink the available seed pool for germination.

### Scenario 2 – Low control efficacy for seed production

In the low control efficacy level as reflected by the 2018 fecundity rates, waterhemp population densities would increase rapidly in all rotations, but most quickly in the 2-year rotation (Figure 5). The population increase in the 3-year rotation under low herbicide corn weed management was similar to that of the 4-year rotation. Even though were all increasing the partition of seedbanks differed between rotations. Within the same rotation, a consistent pattern of top : bottom ratio of seed densities was observed between two corn weed management regimes. In the 2-year rotation, a large portion of the seedbanks was in the 0-2 cm soil stratum; in the 3-year rotation, the top and bottom soil strata were fairly evenly populated; and in the 4-year rotation, the majority of the seeds was in the bottom stratum.

The oat phase of the 3-year rotation (O3) and the alfalfa phase of the 4-year rotation (A4) offered opportunities for decreasing , which was not possible in any other crop phases in the three examined rotations. However, the declines in ’s in O3 ( = 0.60 and = 0.56) and A4 ( = 0.70 and = 0.54) were not strong enough to deplete seed replenishment occurring in the corn phase ( = 5.56, = 1.20, = 172.81, and = 87.14) and soybean phase ( = 13360.78, = 4361.91, = 80.51, and = 10.18).

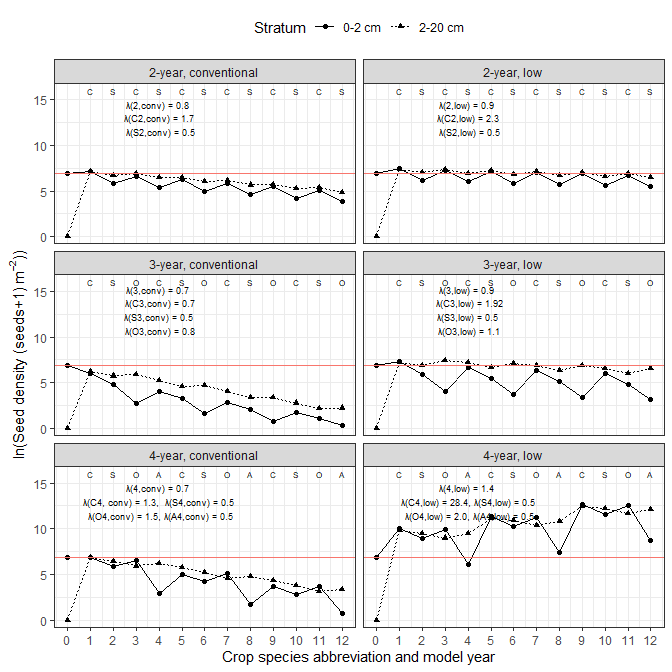


Figure 3: Scenario 1: Changes of seed densities in two soil strata after 12 model years in three rotations (2-year, 3-year, and 4-year) crossed with two corn weed management programs (conventional and low herbicide). The model started at year 0 with 1000 and 0 seeds per meter squared in the top (0-2 cm) and bottom (2-20 cm) soil strata, respectively. The red horizontal line shows the number of seeds in the top stratum at the beginning of the model clock. The annualized population growth rates are followed by their variances in brackets. The model years are labeled with the main crop species names’ abbreviations: C - corn, S - soybean, O - oat, and A - alfalfa.

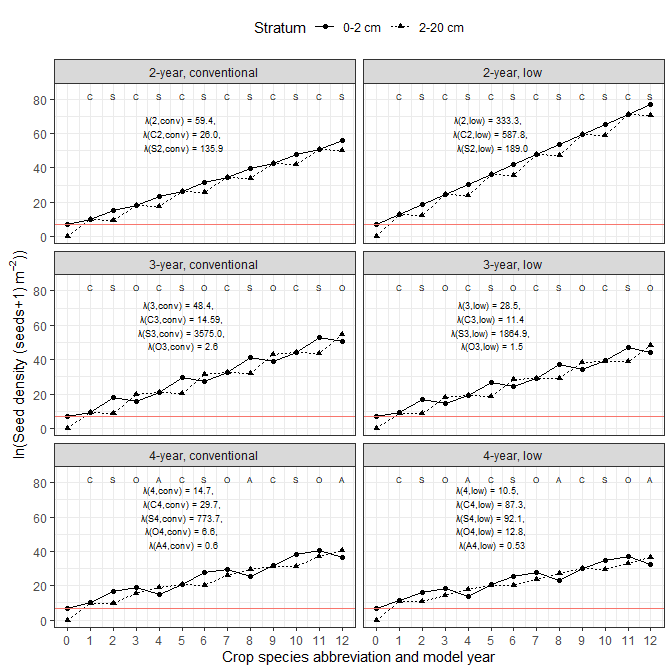


Figure 4: Scenario 2: Changes of natural-logarithm of seed densities in two soil strata after 12 model years in three rotations (2-year, 3-year, and 4-year) crossed with two corn weed management programs (conventional and low herbicide). Seed densities were natural-logarithm transformed because of scales. The model started at year 0 with 1000 and 0 seeds per meter squared in the top (0 - 2 cm) and bottom (2 - 20 cm) soil strata, respectively. The red horizontal line shows the number of seeds at the top stratum at the beginning of the model clock. The annualized population growth rates are followed by their variances in brackets. The model years are labeled with the main crop species names’ abbreviations: C - corn, S - soybean, O - oat, and A - alfalfa.

## Simulation

### Seed production threshold

Keeping all the input matrices, except the seed production matrix (Bf), as in the population projection exercise, the seed production thresholds presented here were converted from seeds plant-1 to seeds m-2.

Under both corn weed management regimes, the 4-year rotation was projected to tolerate higher seed production in the corn phase than the 3-year and 2-year rotations could (Figure 5). The lower seed production was in the cool season crops; the higher seed production could be tolerated in the warm-season crops. The relative seed production tolerance of the 3-year rotation differed between two corn weed management regimes (Figure 5): 863 seeds m-2 under conventional corn weed management and 4482 seeds m-2 under low herbicide corn weed management. However, regardless of the corn weed management regime, the more diverse rotation could tolerate lower seed production in the soybean phase than the 2-year rotation.

Using the population dynamics demonstrated in Scenario 1, an initial population density of 10000 seeds m would remain stable if the first three waterhemp cohorts in C2 seed production was capped at 1464 seeds mand 1402 seeds min conventional and low herbicide management, respectively; the first three waterhemp cohorts in S2 seed production was capped at 39843 seeds mand 1070 seeds m in conventional and low herbicide management, respectively.

While it was not necessary to expose the waterhemp cohorts 4 and beyond to control measures in the corn and soybean phases of the 2-year rotation, it would be necessary to expand weed control measures after the first three waterhemp cohorts in corn and soybean phases in the 3-year rotation with conventional corn weed management and the 4-year rotation under both corn weed management regimes to control the plants that emerged later but were of high reproductive potentials. As no herbicide was applied in the cool-season crops, weed control efficacy in those crop environments would be largely dependent on the crop’s competitiveness, such as canopy closure, allelochemical exudation and retention, physical weed control, such as post-harvest stubble clipping timing frequency in O3 and hay cut frequency in A4), and granivore activity enhancement in O3, O4, and A4.

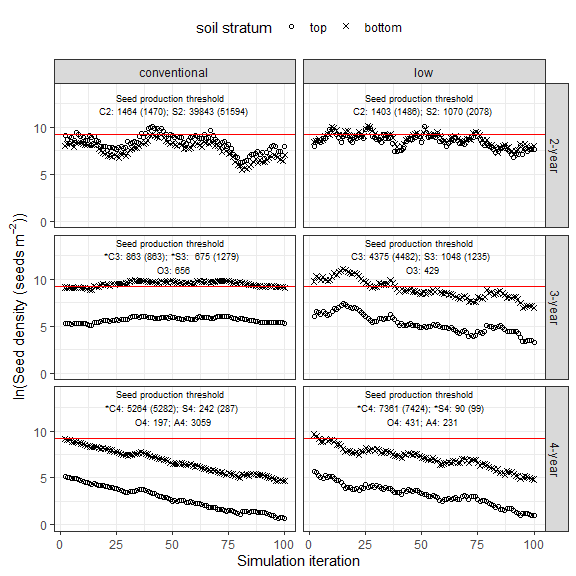


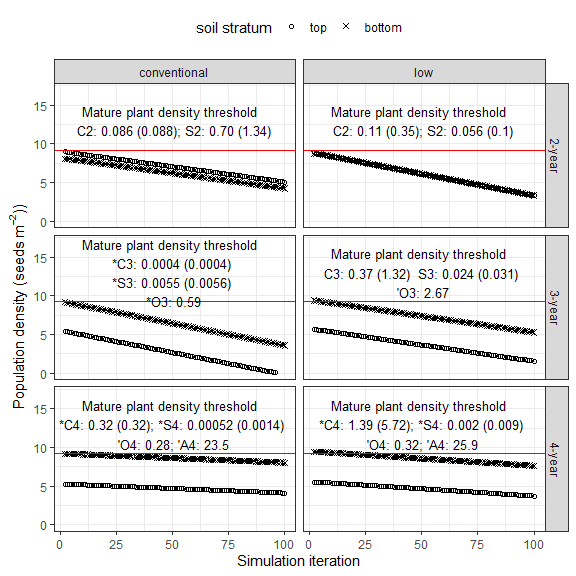
Figure 5: Population size at the end of a rotation cycle over 100 rotational cycles (the 2-year rotation ended at the soybean phase, the 3-year rotation ended at the oat phase, and the 4-year rotation ended at the alfalfa phase). All simulations started with a seed column of 10000 female seeds in the top 0 - 2 cm soil stratum and 0 female seeds in the bottom 2 - 20 cm soil stratum. . The crop phases marked with an inverted comma (’) are where no additional control was applied. It was expected that no waterhemp cohorts in any crop environments but only the cohorts 1 through 3 in corn and soybean were manipulated to find the seed production thresholds. However, additional control efficacy was needed in some crop phases outside of the expected group to reduce seed production potentials. The crop phases marked with an asterisk (\*) are where control measures extended beyond waterhemp cohort 3 would be necessary. The relationships between aboveground mass and fecundity in Nguyen and Liebman (2022a) were used to estimate cohort-based fecundity. Each panel was annotated with the average fecundity thresholds for the first three waterhemp cohorts in corn and soybean, followed by the whole crop phase of all the phases occurring in the same rotation. The red horizontal line marks the seedbank density at λ= 1.

### Mature plant density threshold

Keeping all the input matrices, except the seed production matrix (Bs), as in the population projection exercise, the mature plant densities presented here are plant m-2 immediately before seed production.

The patterns shown in mature plant density thresholds are similar to seed production thresholds (Figure 6). Regardless of the corn weed management program, the 4-year rotation could tolerate higher mature waterhemp densities in the corn phase than the 3-year and 2-year rotations.

Among all the cool-season crops, no additional control efficacy was needed, except in the oat phase of the 3-year rotation that followed conventional herbicide corn weed management. More aggressive stubble clipping after oat harvest would be necessary in this case, as 99.999% control efficacy in the corn and soybean phases was insufficient to stabilize the population size. Even though the simulation showed that additional control efficacy might not be necessary in the oat and alfalfa phases of the 4-year rotation, it might be required in reality because achieving 0.00052 plants m-2 to 0.002 plants m-2 (equivalent to above 99.999% efficacy with respect to density) might be impossible. Similarly, the mature waterhemp plant density in O3 that followed conventional corn weed management would need to be reduced to lower than 0.59 plants m-2.



*Figure 6: Population size at the end of a rotation cycle over 100 rotational cycles (the 2-year rotation ended at the soybean phase, the 3-year rotation ended at the oat phase, and the 4-year rotation ended at the alfalfa phase). All simulations started with a seed column of 10000 female seeds in the top 0 - 2 cm soil stratum and 0 female seed in the bottom 2 - 20 cm soil stratum. The simulation applied improved weed control efficacy on cohorts 1 through 3 in corn and soybean only. The relationships of aboveground mass and fecundity in Nguyen and Liebman (2022a) were used to estimate cohort-based fecundity. It was expected that no waterhemp cohorts in any crop environments but only the cohorts 1 through 3 in corn and soybean had their survival rates manipulated to find the mature plant density thresholds. However, additional control efficacy was needed in some crop phases outside of the expected groups to reduced the mature plant densities. The crop phases marked with an asterik (\*) are where control measures extended beyond the expected cohorts within the expected crop environments would be neccessary. Each panel was annotated with the average fecundity thresholds for the first three waterhemp cohorts in corn and soybean followed by the whole crop phase. The crop phases marked with an inverted comma (’) are where no additional control was applied. The red horizontal line marks λ = 1.*

# Conclusion

Delayed but steady emergence (Tables 3 and 4, Figure 2) in the cool-season crop environments decreased population fecundity in the oat and alfalfa phases and thus, accelerated seedbank size reduction in Scenario 1 and slowed seedbank size increment in Scenario 2.

The cohort-based female survival rates at the experiment site were not realistically estimated due to the small sample size in a high-efficacy weed management program (Table A1). Future experiments should focus on assessing cohort-based female survival rates in cool-season crop environments.

The hypothesis that “extending a conventional 2-year rotation of corn and soybean with cool-season crops can accelerate soil seedbank depletion” was supported by Scenario 1 in the projection exercise and the follow-up simulation. Unlike giant foxtail, whose bottleneck point in the life cycle was the overwinter seed survival rates (Davis, 2002), waterhemp’s bottleneck point in its life cycle was seedling emergence rate and seedling to maturity survival success rate. An elasticity analysis (outputs not shown) suggested that fecundity overrode all the population dynamics and dictated the population growth. Even though the elasticity analysis was not informative, it was consistent with waterhemp’s competitiveness, that is, even with an extremely low survival rate, if the early emerged plants were unaffected by weed control programs, either through herbicide resistance or escaped from cultivation, and completed their life cycle, a small number of large, prolific female plants would sufficiently replenish the soil seedbank.

A reduction in the mass of applied herbicide active ingredients (Nguyen and Liebman, 2022b) was not coincident with the population decline in Scenario 1 () but did coincide with population increases in Scenario 2 (). Even though population sizes were projected to increase in Scenario 2, the increase rates were lower in the extended rotations. Considering Scenario 2, it would be useful to examine how many years of continuous overwinter crops would be necessary and which cool-season crop species would be most efficient in decreasing waterhemp after steady seedbank replenishment. Such an investigation is needed because even if the increased abundance of waterhemp and other weed species has not been observed at the experiment site (Nguyen and Liebman, 2022b), an abundant seedbank of a highly competitive weed species harbors risks of weed outbreaks.

The weed control pressure for the corn and soybean phases could be lessened with more extended rotations as waterhemp plants of higher reproductive potentials in cohorts 1 through 3 could be tolerated in the 3-year and 4-year rotations than in the 2-year rotation. This higher tolerance can be attributed to the weed control effects by extending a cropping system of corn and soybean with cool-season crops. The more stable moisture provided by the alfalfa crop environment (compared with other crop environments) might be responsible for the steady and higher relative abundant emergence rates in A4. Empirical measurement in alfalfa is needed to test the relatively high emergence rates (approximately 45% of the top 0 – 2 cm soil seedbank) reported in this study.

Waterhemp seed production and mature plant density thresholds complement each other well in simulating required control efficacy. Using plant density alone would cause erroneous estimations for a species with highly variable individual sizes. In addition, its high relative growth rate and opportunistic germination patterns can allow few plants to escape control measures and establish high reproductive potential. As waterhemp fecundity was manipulated mostly for cohorts 1 through 3 in corn and soybean environments only, it is implied that: 1) if efforts were made to severely suppress waterhemp in corn and soybean phases, no additional weed management might be needed in the oat and alfalfa phases, and thus, even the big waterhemp plants in oat and alfalfa phases might not require attention; and 2) conversely if efforts in suppressing waterhemp cohorts 1 through 3 failed in the warm-season crop phases, either intervention on the waterhemp cohorts 4 and beyond in the warm-season crop phases or higher control efficacy in the cool-season crop phases would be necessary.

Similarly, as waterhemp mature plant densities were manipulated for when weed control measures would be feasible in our experiment design (a few weeks after corn and soybean sowing, after oat harvest, or alfalfa readiness and weather-permitting hay cut), it is implied that effective and efficient weed management when possible was crucial to keep the population of concern from increasing. In our experiment, the oat, red clover, and alfalfa in the 3-year and 4-year rotations allowed for more frequent physical weed control at stages that waterhemp could be most vulnerable to severe reproductive potential loss. A more comprehensive simulation combining the seed production and mature plant density thresholds could address a suite of more diverse population compositions in the field.

## Appendix

### A – Empirically measured data

#### Seed densities at the top and bottom soil strata

## ANOVA of Crop ID x Corn weed management effects on AMATA seedbank density at the 0-2 cm soil stratum  
AMATA\_female\_top\_lm <- lm(log(AMATA\_total\_viable\_density + 1) ~ Block +   
 Crop\_ID \* Corn\_weed\_management,   
 data = top\_stratum\_female)  
  
  
## ANOVA table of female seedbank density at the 0-2 cm soil stratum  
AMATA\_female\_top\_emm\_log <- emmeans(AMATA\_female\_top\_lm,   
 c("Crop\_ID" , "Corn\_weed\_management"))  
  
joint\_tests(AMATA\_female\_top\_emm\_log )

## model term df1 df2 F.ratio p.value  
## Crop\_ID 8 51 14.638 <.0001  
## Corn\_weed\_management 1 51 0.998 0.3225  
## Crop\_ID:Corn\_weed\_management 8 51 0.343 0.9445

## ANOVA of Crop ID x Corn weed management effects on AMATA seedbank density at the 2-20 cm soil stratum  
AMATA\_female\_bottom\_lm <- lm(log(AMATA\_total\_viable\_density + 1) ~ Block +   
 Crop\_ID \* Corn\_weed\_management,   
 data = bottom\_stratum\_female)  
   
  
## ANOVA table of female seedbank density at the 2-20 cm soil stratum  
AMATA\_female\_bottom\_emm\_log <- emmeans(AMATA\_female\_bottom\_lm, c("Crop\_ID" , "Corn\_weed\_management"))  
  
joint\_tests(AMATA\_female\_bottom\_emm\_log)

## model term df1 df2 F.ratio p.value  
## Crop\_ID 8 51 8.812 <.0001  
## Corn\_weed\_management 1 51 0.482 0.4908  
## Crop\_ID:Corn\_weed\_management 8 51 0.288 0.9669



Figure A1: Diagnosis plots for the effects of crop identity and crop weed management on the seedbank densities at the top (A) and bottom (B) soil strata

#### Seedbank density from 2014 through 2019



Figure A2: Dead and viable seedbank density from 2014 through 2019. 2018 seedbank density was not evaluated due to weather adversity.

#### Emergence pattern and timing in different crop environments

## Did crop identity and corn weed management affect waterhemp's emergence pattern in 2019?  
emerge\_cohort\_19\_gls <- gls(log(eu\_female\_cohort\_Density\_begin+1) ~ Block +   
 Crop\_ID\*Corn\_weed\_management + Cohort +  
 Crop\_ID:Cohort + Corn\_weed\_management:Cohort,  
 correlation=corCompSymm(form=~1 | bt),  
 weights=varIdent(form= ~1 | Cohort),  
data = density\_emerge\_19)  
  
 joint\_tests(emerge\_cohort\_19\_gls)

## model term df1 df2 F.ratio p.value  
## Block 3 68.42 2.793 0.0468  
## Crop\_ID 8 54.23 222.641 <.0001  
## Corn\_weed\_management 1 54.23 0.518 0.4749  
## Cohort 5 75.61 438.355 <.0001  
## Crop\_ID:Corn\_weed\_management 8 68.42 0.956 0.4772  
## Crop\_ID:Cohort 40 75.61 46.683 <.0001  
## Corn\_weed\_management:Cohort 5 75.61 1.569 0.1790

## Did crop identity and corn weed management affect waterhemp's emergence pattern in 2020?  
#   
emerge\_cohort\_20\_gls <- gls(log(cohort\_female\_Seedling\_density +1) ~ Block +   
 Crop\_ID\*Corn\_weed\_management + Cohort +  
 Crop\_ID:Cohort + Corn\_weed\_management:Cohort,  
 correlation=corCompSymm(form=~1 | bt),  
 weights=varIdent(form= ~1 | Cohort),  
data=cohort\_emerge\_20\_first\_six )  
  
 joint\_tests(emerge\_cohort\_20\_gls)

## model term df1 df2 F.ratio p.value  
## Block 3 65.97 2.376 0.0779  
## Crop\_ID 8 57.25 9.890 <.0001  
## Corn\_weed\_management 1 57.25 13.732 0.0005  
## Cohort 5 66.34 40.266 <.0001  
## Crop\_ID:Corn\_weed\_management 8 65.97 5.920 <.0001  
## Crop\_ID:Cohort 40 66.34 11.498 <.0001  
## Corn\_weed\_management:Cohort 5 66.34 5.185 0.0004

## Did crop identity and corn weed management affect waterhemp's first emergence timing in 2019?  
Julian\_cohort1\_19\_lm <- lm(Julian\_day ~ Block +   
 Crop \* Corn\_weed\_management,  
data = cohort1\_2019)   
  
joint\_tests(Julian\_cohort1\_19\_lm)

## model term df1 df2 F.ratio p.value  
## Block 3 61 0.000 1.0000  
## Crop 3 61 458.187 <.0001  
## Corn\_weed\_management 1 61 0.000 1.0000  
## Crop:Corn\_weed\_management 3 61 0.000 1.0000

## Did crop identity and corn weed management affect waterhemp's first emergence timing in 2020?  
Julian\_cohort1\_20\_lm <- lm(Julian\_day ~ Block +   
 Crop\*Corn\_weed\_management,  
 data=cohort1\_2020)  
  
joint\_tests(Julian\_cohort1\_20\_lm )

## model term df1 df2 F.ratio p.value  
## Block 3 61 10.170 <.0001  
## Crop 3 61 64217.940 <.0001  
## Corn\_weed\_management 1 61 0.000 1.0000  
## Crop:Corn\_weed\_management 3 61 0.000 1.0000



Figure A3: Diagnosis plots for the effects of crop identity and corn weed management on the seedbank densities at the top (A) and bottom (B) soil strata

#### 2019 female survival rate by cohort

Table A1: Point-estimates of 2019 seedling to maturity survival rates by cohort. Some zeroes are due to rounding.

|  |  | Cohort | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Crop ID | Corn weed management | 1 | 2 | 3 | 4 | 5 | 6 |
| C2 | conventional | 0.17 | 0.10 | 0.19 | 0.46 | 0.50 | 0.50 |
| C2 | low | 0.00 | 0.15 | 0.32 | 0.43 | 0.17 | 0.00 |
| S2 | conventional | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S2 | low | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| C3 | conventional | 0.15 | 0.25 | 0.34 | 0.53 | 0.00 | 0.67 |
| C3 | low | 0.02 | 0.20 | 0.33 | 0.23 | 0.00 | 1.00 |
| S3 | conventional | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S3 | low | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O3 | conventional | 0.04 | 0.08 | 0.01 | 0.39 | 0.00 | 0.00 |
| O3 | low | 0.03 | 0.02 | 0.03 | 0.07 | 0.04 | 0.00 |
| C4 | conventional | 0.38 | 0.26 | 0.42 | 0.50 | 0.00 | 0.00 |
| C4 | low | 0.02 | 0.24 | 0.37 | 0.30 | 0.00 | 0.00 |
| S4 | conventional | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| S4 | low | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| O4 | conventional | 0.15 | 0.10 | 0.28 | 0.22 | 0.33 | 0.22 |
| O4 | low | 0.07 | 0.04 | 0.09 | 0.13 | 0.29 | 0.08 |
| A4 | conventional | 0.06 | 0.06 | 0.17 | 0.02 | 0.06 | 0.00 |
| A4 | low | 0.08 | 0.06 | 0.10 | 0.14 | 0.25 | 0.00 |

### 

### B - Matrix assembly

The structure of all periodic matrices used in the two control efficacy levels is listed below. All numbers are female-only. Each theoretical matrix for a sub-annual period is followed by the set of matrices used in that sub-annual period. The abbreviate row and column names are:  
- s\_t: seed at the top stratum (0 - 2 cm),  
- s\_b: seed at the bottom stratum (2 - 20 cm),  
- p\_co\_1 through p\_co\_6: plant cohort 1 through 6.

#### Published literature data

##### Pre-planting tillage induced vertical redistribution of seeds

The only non-zeroes section of the pre-planting tillage-induced vertical redistribution of seeds is . ’s were resized from the raw data of Seed Chaser (Spokas et al., 2007), a simulation program that estimates vertical seed movement after various types of tillage: the proportion of seeds staying at their original soil stratum, and , or move to another stratum, and . The original matrices in Spokas et al. (2007) were resized to 2 x 2 by summing over all the elements within each of the four sections, i.e., top left 2 x 2, bottom left 18 x 2, top right 2 x 18, and 18x18, and divide each of the i x 2 summations by the summation of the 20 x 2 left section, and each of the i x 18 summations by the summation of the 20 x 2 right section.

No-till is represented by an identical matrix, , after Cousens and Moss (1990). A field cultivator was applied before planting corn (C2, C3, and C4), soybean (S2, S3, and S4), and oat (O3 and O4). No-tillage was applied before alfalfa (A4) because alfalfa intercropped with oat in the 4-year rotation (O4) was kept overwinter and grown as a sole crop in the following year.

The same pre-planting tillage regimes were applied in 2018 and 2019.

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.15 0 0 0 0 0 0  
## s\_b 0.41 0.85 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0

##### In-season survival of seeds and seedlings

The matrix is comprised of seed survival rates at the and plant survival rates at the sections, respectively.

The section’s diagonal ( and ) were filled with survival rates adapted from equations and (Figures 1 and 3, Sosnoskie et al., 2013) for the top and bottom layers. The values of x were assigned at 6 months for all crop environments. We settled at 6 months despite the complexity in tillage timing and method, light and humidity conditions, and granivores’ activities at individual crop environments for simplicity. In reality, the burial length can interact with any crop management activity and deliver different germination and emergence results.

The empirically measured data for seedling survival were deemed unrealistically (Appendix) low as compared to the literature, so Nordby and Hartzler's (2004) results were used for corn, and Hartzler et al. (2004)’s results were used for soybean crop environments. The seedling survival rates by cohort () were assigned such that the earlier cohorts had a lower survival rate in the oat crop environment; and those in the alfalfa crop environment were evenly low in all cohorts. These estimated numbers were based on a suggestion that cool-season crop environments can inhibit warm-season weed species growth (Nguyen and Liebman, 2022b and citations given there).

The same summer survival rates were used in 2018 and 2019.

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.1 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.1 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.5 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.5  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.1 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.1 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.5 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.5  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.48 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.48 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.04 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.04 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.5 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.5 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.9 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.9  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.5 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.5 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.9 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.9  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.5 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.5 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.9 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.9  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.0 0.0 0.0 0.0 0.0 0.0  
## s\_b 0.00 0.74 0.0 0.0 0.0 0.0 0.0 0.0  
## p\_co\_1 0.00 0.00 0.1 0.0 0.0 0.0 0.0 0.0  
## p\_co\_2 0.00 0.00 0.0 0.1 0.0 0.0 0.0 0.0  
## p\_co\_3 0.00 0.00 0.0 0.0 0.5 0.0 0.0 0.0  
## p\_co\_4 0.00 0.00 0.0 0.0 0.0 0.5 0.0 0.0  
## p\_co\_5 0.00 0.00 0.0 0.0 0.0 0.0 0.9 0.0  
## p\_co\_6 0.00 0.00 0.0 0.0 0.0 0.0 0.0 0.9  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0.00 0.00 0.00 0.00 0.00 0.00  
## s\_b 0.00 0.74 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0.00 0.00 0.84 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0.00 0.00 0.00 0.84 0.00 0.00 0.00 0.00  
## p\_co\_3 0.00 0.00 0.00 0.00 0.26 0.00 0.00 0.00  
## p\_co\_4 0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00  
## p\_co\_5 0.00 0.00 0.00 0.00 0.00 0.00 0.01 0.00  
## p\_co\_6 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.01

##### Post-harvest tillage induced vertical redistribution of seeds post-harvest tillage

The compilation of was similar to that of . Chisel plowing was applied after corn was harvested in the C2, C3, and C4 treatments, no-till was applied after harvests in the S2, S3, S4, and O4 treatments, and moldboard plowing was applied at the end of the O3 and A4 phases.

The same post-harvest tillage regimes were applied in 2018 and 2019.

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.02 0.07 0 0 0 0 0 0  
## s\_b 0.98 0.93 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.02 0.07 0 0 0 0 0 0  
## s\_b 0.98 0.93 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.59 0.1 0 0 0 0 0 0  
## s\_b 0.41 0.9 0 0 0 0 0 0  
## p\_co\_1 0.00 0.0 0 0 0 0 0 0  
## p\_co\_2 0.00 0.0 0 0 0 0 0 0  
## p\_co\_3 0.00 0.0 0 0 0 0 0 0  
## p\_co\_4 0.00 0.0 0 0 0 0 0 0  
## p\_co\_5 0.00 0.0 0 0 0 0 0 0  
## p\_co\_6 0.00 0.0 0 0 0 0 0 0  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.02 0.07 0 0 0 0 0 0  
## s\_b 0.98 0.93 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.02 0.07 0 0 0 0 0 0  
## s\_b 0.98 0.93 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0 0 0 0 0 0  
## s\_b 0 1 0 0 0 0 0 0  
## p\_co\_1 0 0 0 0 0 0 0 0  
## p\_co\_2 0 0 0 0 0 0 0 0  
## p\_co\_3 0 0 0 0 0 0 0 0  
## p\_co\_4 0 0 0 0 0 0 0 0  
## p\_co\_5 0 0 0 0 0 0 0 0  
## p\_co\_6 0 0 0 0 0 0 0 0

##### Overwinter survival

The compilation of matrix was similar to that of , using equations and (Figures 1 and 3, Sosnoskie et al., 2013).

The same overwinter survival rates were used in 2018 and 2019. Some zero values were due to rounding.

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 0.66 0.00 0 0 0 0 0 0  
## s\_b 0.00 0.74 0 0 0 0 0 0  
## p\_co\_1 0.00 0.00 0 0 0 0 0 0  
## p\_co\_2 0.00 0.00 0 0 0 0 0 0  
## p\_co\_3 0.00 0.00 0 0 0 0 0 0  
## p\_co\_4 0.00 0.00 0 0 0 0 0 0  
## p\_co\_5 0.00 0.00 0 0 0 0 0 0  
## p\_co\_6 0.00 0.00 0 0 0 0 0 0

#### Empirically measured data

##### Seedling recruitment

The emergence proportions calculated from step 5 here are positioned on the first column of block in the matrix . represents the proportion of non-emerging seeds.

The raw proportion of seedling emergence from the top 0 – 2 cm soil seedbank stratum in each crop identity crossed with the corn weed management regime was calculated with the following steps:

1 - Estimate the 0-2 cm and 2-20 cm seedbank densities with the soil seedbank samples collected before post-harvest tillage. A seed column at a particular sub-annual period is comprised of the 0-2 cm and 2-20 cm soil stratum seed densities, .

From steps 2 through 4, the seed column in sub-period h, , was transitioned from one period to the next with the general matrix multiplication of by Caswell (2001).

2 - Estimate post-harvest tillage induced vertical seed redistribution with resized Seed Chaser (Spokas et al., 2007) chisel and moldboard plowing matrices, as detailed in the *Post-harvest tillage induced vertical seed movement*, to yield

3 - Adapt overwinter survival rates as previously explained in thee *Overwinter survival section* and apply it on to yield . Corn weed management did not affect waterhemp’s first cohort emergence in the same crop environment (Appendix), so the same value of was used for the same crop identity.

4 - Estimate pre-planting tillage-induced seed vertical redistribution with resized Seed Chaser (Spokas et al., 2007) field cultivator matrix, similar to step 2 to yield .

5 - Divide the seedling density in each cohort, , by , the top soil stratum seed density to yield .

Even though the herbicide resistance profile at our experiment was unknown, the values from step 5 turned out to be unrealistically low in all crop envrionments except alfalfa and unrealistically high in alfalfa as compared to the literature (Buhler and Hartzler 2001, Schutte and Davis 2014). 5% of the waterhemp seeds in a soil seedbank of 5 cm deep undisturbed mechanically in the first burial year and unexposed to herbicides throughout the experiment emerged a year after seed burial (Buhler and Hartzler 2001). Annually, 23.5% +/- 16.6% sd of waterhemp seeds that were not treated with herbicides and undisturbed mechanically emerged from the top 1 cm soil layer (Schutte and Davis 2014). Mesotrione applied at 75 g ha-1 rate was 76% and 96% efficacious against *A retroflexus* L grown in corn susceptible and resistant to atrazine, respectively (Sutton et al., 2002). On average, the Thiencarbazone-methyl + isoxaflutole mixture was 93.5% efficacious, and mesotrione was 70.75% efficacious against *A. palmeri* grown in corn (Janak and Grirchar, 2016).

We combined the findings on other *Amaranthus* species from Sutton et al., (2002) and Janak and Grichar (2016) for herbicide efficacy and from Buhler and Hartzler (2001) and Schutte and Davis (2014) for herbicide-unexposed germinants’ emergence and set a uniform germination rate in all the crop identity crossed with corn weed management at 20%. The remaining seedbank density in the 0 - 2 cm soil stratum is calculated using the following equation:

where,  
 is the remaining seedbank density after seed germination

is the seed density in the top 0 - 2 cm soil stratum upon completion of pre-planting tillage,

is the proportion of germinated seeds,

is the proportion of germinated seeds that successfully emerge as seedlings, and

is the proportion of germinated seeds that were killed by weed control measures.

is filled in the [1,1] position of the seedling recruitment matrix (). The cohort-specific emergence rates ( through ) were adjusted from the raw data ( with ) to reflect 5% emergence success rate (equivalent to ) in crop environments that received pre-emergence herbicides (C2, C3 and C4 under conventional weed management and all the S2, S3, and S4 (Table 1, Nguyen and Liebman 2022b)), 100% emergence success rate (equivalent to ) in the crop environments that received post-emergence herbicides (C2, C3 and C4 under low herbicide weed management, (Table 1, Nguyen and Liebman 2022b)) and 50% emergence success rate (equivalent to ).

Table A4: Estimated and adjusted seedling emergence proportion of the top 0 - 2 cm soil stratum and the whole seedbank (20 cm deep) using 2019 stratified soil seedbank densities and 2020 seedling emergence densities.

|  |  | Estimated total emergence proportion from | |  | Adjusted total emergence proportion from | |
| --- | --- | --- | --- | --- | --- | --- |
| Crop ID | Corn weed management | top 0 - 2 cm | whole seedbank | adjuster | top 0 - 2 cm | whole seedbank |
| C2 | conventional | 0.0024 | 0.0008 | 4.1310 | 0.01 | 0.0031 |
| C2 | low | 0.0109 | 0.0033 | 18.2760 | 0.20 | 0.0606 |
| S2 | conventional | 0.0637 | 0.0179 | 0.1570 | 0.01 | 0.0028 |
| S2 | low | 0.0248 | 0.0086 | 0.4035 | 0.01 | 0.0035 |
| C3 | conventional | 0.0073 | 0.0017 | 1.3686 | 0.01 | 0.0024 |
| C3 | low | 0.0298 | 0.0067 | 6.7167 | 0.20 | 0.0449 |
| S3 | conventional | 0.0374 | 0.0063 | 0.2676 | 0.01 | 0.0017 |
| S3 | low | 0.0234 | 0.0048 | 0.4275 | 0.01 | 0.0021 |
| O3 | conventional | 0.0030 | 0.0005 | 33.1797 | 0.10 | 0.0167 |
| O3 | low | 0.0033 | 0.0005 | 30.3782 | 0.10 | 0.0165 |
| C4 | conventional | 0.0587 | 0.0121 | 0.1704 | 0.01 | 0.0021 |
| C4 | low | 0.1997 | 0.0404 | 1.0016 | 0.20 | 0.0405 |
| S4 | conventional | 0.0010 | 0.0002 | 9.6448 | 0.01 | 0.0018 |
| S4 | low | 0.0011 | 0.0002 | 9.3056 | 0.01 | 0.0019 |
| O4 | conventional | 0.0009 | 0.0004 | 110.0551 | 0.10 | 0.0433 |
| O4 | low | 0.0009 | 0.0004 | 107.2800 | 0.10 | 0.0474 |
| A4 | conventional | 0.3926 | 0.0126 | 0.2547 | 0.10 | 0.0032 |
| A4 | low | 0.3517 | 0.0108 | 0.2843 | 0.10 | 0.0031 |

The same emergence rates were used in Scenario 1 (high control efficacy concerning seed production) and Scenario 2 (low control efficacy concerning mature plant density).

## $A4\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0196957501 0 0 0 0 0 0 0  
## [4,] 0.0442930181 0 0 0 0 0 0 0  
## [5,] 0.0003761959 0 0 0 0 0 0 0  
## [6,] 0.0335678394 0 0 0 0 0 0 0  
## [7,] 0.0016212218 0 0 0 0 0 0 0  
## [8,] 0.0004459747 0 0 0 0 0 0 0  
##   
## $A4\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0196449014 0 0 0 0 0 0 0  
## [4,] 0.0438292593 0 0 0 0 0 0 0  
## [5,] 0.0006496612 0 0 0 0 0 0 0  
## [6,] 0.0332841223 0 0 0 0 0 0 0  
## [7,] 0.0018737871 0 0 0 0 0 0 0  
## [8,] 0.0007182687 0 0 0 0 0 0 0  
##   
## $C2\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 8.192085e-04 0 0 0 0 0 0 0  
## [4,] 9.126203e-03 0 0 0 0 0 0 0  
## [5,] 1.364711e-05 0 0 0 0 0 0 0  
## [6,] 1.364711e-05 0 0 0 0 0 0 0  
## [7,] 1.364711e-05 0 0 0 0 0 0 0  
## [8,] 1.364711e-05 0 0 0 0 0 0 0  
##   
## $C2\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.800000000 0 0 0 0 0 0 0  
## [2,] 0.000000000 1 0 0 0 0 0 0  
## [3,] 0.027154679 0 0 0 0 0 0 0  
## [4,] 0.136315915 0 0 0 0 0 0 0  
## [5,] 0.012822644 0 0 0 0 0 0 0  
## [6,] 0.009270740 0 0 0 0 0 0 0  
## [7,] 0.007394421 0 0 0 0 0 0 0  
## [8,] 0.007041600 0 0 0 0 0 0 0  
##   
## $C3\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 9.922701e-04 0 0 0 0 0 0 0  
## [4,] 8.814370e-03 0 0 0 0 0 0 0  
## [5,] 9.790507e-06 0 0 0 0 0 0 0  
## [6,] 1.639881e-04 0 0 0 0 0 0 0  
## [7,] 9.790507e-06 0 0 0 0 0 0 0  
## [8,] 9.790507e-06 0 0 0 0 0 0 0  
##   
## $C3\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.800000000 0 0 0 0 0 0 0  
## [2,] 0.000000000 1 0 0 0 0 0 0  
## [3,] 0.029273645 0 0 0 0 0 0 0  
## [4,] 0.127406335 0 0 0 0 0 0 0  
## [5,] 0.012067914 0 0 0 0 0 0 0  
## [6,] 0.018882378 0 0 0 0 0 0 0  
## [7,] 0.006186034 0 0 0 0 0 0 0  
## [8,] 0.006183694 0 0 0 0 0 0 0  
##   
## $C4\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 9.614807e-04 0 0 0 0 0 0 0  
## [4,] 8.998794e-03 0 0 0 0 0 0 0  
## [5,] 9.931386e-06 0 0 0 0 0 0 0  
## [6,] 9.931386e-06 0 0 0 0 0 0 0  
## [7,] 9.931386e-06 0 0 0 0 0 0 0  
## [8,] 9.931386e-06 0 0 0 0 0 0 0  
##   
## $C4\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.800000000 0 0 0 0 0 0 0  
## [2,] 0.000000000 1 0 0 0 0 0 0  
## [3,] 0.029999699 0 0 0 0 0 0 0  
## [4,] 0.138718132 0 0 0 0 0 0 0  
## [5,] 0.010246571 0 0 0 0 0 0 0  
## [6,] 0.007991206 0 0 0 0 0 0 0  
## [7,] 0.006630544 0 0 0 0 0 0 0  
## [8,] 0.006413847 0 0 0 0 0 0 0  
##   
## $O3\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0207984844 0 0 0 0 0 0 0  
## [4,] 0.0380865465 0 0 0 0 0 0 0  
## [5,] 0.0243725123 0 0 0 0 0 0 0  
## [6,] 0.0155099704 0 0 0 0 0 0 0  
## [7,] 0.0010180758 0 0 0 0 0 0 0  
## [8,] 0.0002144107 0 0 0 0 0 0 0  
##   
## $O3\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0205526989 0 0 0 0 0 0 0  
## [4,] 0.0359709847 0 0 0 0 0 0 0  
## [5,] 0.0237401807 0 0 0 0 0 0 0  
## [6,] 0.0158361598 0 0 0 0 0 0 0  
## [7,] 0.0029116243 0 0 0 0 0 0 0  
## [8,] 0.0009883517 0 0 0 0 0 0 0  
##   
## $O4\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0137987465 0 0 0 0 0 0 0  
## [4,] 0.0389900716 0 0 0 0 0 0 0  
## [5,] 0.0263769079 0 0 0 0 0 0 0  
## [6,] 0.0151215082 0 0 0 0 0 0 0  
## [7,] 0.0052103905 0 0 0 0 0 0 0  
## [8,] 0.0005023752 0 0 0 0 0 0 0  
##   
## $O4\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.800000000 0 0 0 0 0 0 0  
## [2,] 0.000000000 1 0 0 0 0 0 0  
## [3,] 0.014320464 0 0 0 0 0 0 0  
## [4,] 0.034929111 0 0 0 0 0 0 0  
## [5,] 0.024610470 0 0 0 0 0 0 0  
## [6,] 0.015402596 0 0 0 0 0 0 0  
## [7,] 0.007294458 0 0 0 0 0 0 0  
## [8,] 0.003442901 0 0 0 0 0 0 0  
##   
## $S2\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0072150975 0 0 0 0 0 0 0  
## [4,] 0.0018243253 0 0 0 0 0 0 0  
## [5,] 0.0005192177 0 0 0 0 0 0 0  
## [6,] 0.0001950235 0 0 0 0 0 0 0  
## [7,] 0.0001066115 0 0 0 0 0 0 0  
## [8,] 0.0001397245 0 0 0 0 0 0 0  
##   
## $S2\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 7.733657e-03 0 0 0 0 0 0 0  
## [4,] 1.824108e-03 0 0 0 0 0 0 0  
## [5,] 3.934042e-04 0 0 0 0 0 0 0  
## [6,] 3.801152e-05 0 0 0 0 0 0 0  
## [7,] 5.409597e-06 0 0 0 0 0 0 0  
## [8,] 5.409597e-06 0 0 0 0 0 0 0  
##   
## $S3\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 7.806923e-03 0 0 0 0 0 0 0  
## [4,] 1.557903e-03 0 0 0 0 0 0 0  
## [5,] 3.869985e-04 0 0 0 0 0 0 0  
## [6,] 3.302373e-05 0 0 0 0 0 0 0  
## [7,] 6.735231e-05 0 0 0 0 0 0 0  
## [8,] 1.477994e-04 0 0 0 0 0 0 0  
##   
## $S3\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 7.925166e-03 0 0 0 0 0 0 0  
## [4,] 1.555809e-03 0 0 0 0 0 0 0  
## [5,] 3.623558e-04 0 0 0 0 0 0 0  
## [6,] 1.564556e-06 0 0 0 0 0 0 0  
## [7,] 3.655421e-05 0 0 0 0 0 0 0  
## [8,] 1.185505e-04 0 0 0 0 0 0 0  
##   
## $S4\_conv  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 8.000000e-01 0 0 0 0 0 0 0  
## [2,] 0.000000e+00 1 0 0 0 0 0 0  
## [3,] 7.640143e-03 0 0 0 0 0 0 0  
## [4,] 1.545552e-03 0 0 0 0 0 0 0  
## [5,] 3.835362e-05 0 0 0 0 0 0 0  
## [6,] 2.586504e-04 0 0 0 0 0 0 0  
## [7,] 2.586504e-04 0 0 0 0 0 0 0  
## [8,] 2.586504e-04 0 0 0 0 0 0 0  
##   
## $S4\_low  
## [,1] [,2] [,3] [,4] [,5] [,6] [,7] [,8]  
## [1,] 0.8000000000 0 0 0 0 0 0 0  
## [2,] 0.0000000000 1 0 0 0 0 0 0  
## [3,] 0.0058966010 0 0 0 0 0 0 0  
## [4,] 0.0018654416 0 0 0 0 0 0 0  
## [5,] 0.0008685319 0 0 0 0 0 0 0  
## [6,] 0.0004189521 0 0 0 0 0 0 0  
## [7,] 0.0004189521 0 0 0 0 0 0 0  
## [8,] 0.0005315212 0 0 0 0 0 0 0

##### Plant fecundity

The plant fecundity matrix () had the block’s diagonal filled with 1’s and the first row of the filled with . The 1’s in the block’s diagonal are placeholders to carry the product from the previous matrices over.

Two scenarios of plant fecundity were used. In scenario 1, plant fecundity () in each crop identity crossed with corn weed management was estimated from plant aboveground mass using eighteen equations from Nguyen and Liebman (2022a). In scenario 2, the plants were partitioned into six size-based bins, and their fecundity was summarized as and filled in their relevant positions in the matrix by partitioning. Both practices in scenarios 1 and 2 were based on the assumption that plant size and fecundity decreased as emergence was delayed (Hartzler et al., 2004; Nordby and Hartzler, 2004).

Scenario 1: 2019

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 11.8 5.36 3.4 2.13 1.3 0.64  
## s\_b 0 1 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_1 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_2 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_3 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_4 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_5 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
## p\_co\_6 0 0 0.0 0.00 0.0 0.00 0.0 0.00  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 6.22 3.21 2.26 1.65 1.3 0.88  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 3518.59 615.17 231.49 99.53 29.99 7.69  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 242.93 22.54 12.03 6.81 3.9 2  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.0 0  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.0 0  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 685.16 120.67 37.61 19.81 7.85 2.39  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 105.88 48.51 31.41 24.87 20.11 15.01  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 980.71 643.78 70.33 48.66 6.55 3.09  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 1431.88 969.28 227.07 123.04 38.59 0.98  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 385.14 110.44 57.49 29.61 14.7 3.94  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.0 0.00  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 334.33 202.25 147.01 116.24 86.41 52.36  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 606.39 163.51 81.36 47.65 23.06 8.76  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 963.95 223.23 120.21 69.43 29.84 13.56  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 1.32 0 0 0 0 0  
## s\_b 0 1 0.00 0 0 0 0 0  
## p\_co\_1 0 0 0.00 0 0 0 0 0  
## p\_co\_2 0 0 0.00 0 0 0 0 0  
## p\_co\_3 0 0 0.00 0 0 0 0 0  
## p\_co\_4 0 0 0.00 0 0 0 0 0  
## p\_co\_5 0 0 0.00 0 0 0 0 0  
## p\_co\_6 0 0 0.00 0 0 0 0 0  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 6.99 0 0 0 0 0  
## s\_b 0 1 0.00 0 0 0 0 0  
## p\_co\_1 0 0 0.00 0 0 0 0 0  
## p\_co\_2 0 0 0.00 0 0 0 0 0  
## p\_co\_3 0 0 0.00 0 0 0 0 0  
## p\_co\_4 0 0 0.00 0 0 0 0 0  
## p\_co\_5 0 0 0.00 0 0 0 0 0  
## p\_co\_6 0 0 0.00 0 0 0 0 0  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 8.5 0 0 0 0 0  
## s\_b 0 1 0.0 0 0 0 0 0  
## p\_co\_1 0 0 0.0 0 0 0 0 0  
## p\_co\_2 0 0 0.0 0 0 0 0 0  
## p\_co\_3 0 0 0.0 0 0 0 0 0  
## p\_co\_4 0 0 0.0 0 0 0 0 0  
## p\_co\_5 0 0 0.0 0 0 0 0 0  
## p\_co\_6 0 0 0.0 0 0 0 0 0  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 0.06 0 0 0 0 0  
## s\_b 0 1 0.00 0 0 0 0 0  
## p\_co\_1 0 0 0.00 0 0 0 0 0  
## p\_co\_2 0 0 0.00 0 0 0 0 0  
## p\_co\_3 0 0 0.00 0 0 0 0 0  
## p\_co\_4 0 0 0.00 0 0 0 0 0  
## p\_co\_5 0 0 0.00 0 0 0 0 0  
## p\_co\_6 0 0 0.00 0 0 0 0 0  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 35.45 0 0 0 0 0  
## s\_b 0 1 0.00 0 0 0 0 0  
## p\_co\_1 0 0 0.00 0 0 0 0 0  
## p\_co\_2 0 0 0.00 0 0 0 0 0  
## p\_co\_3 0 0 0.00 0 0 0 0 0  
## p\_co\_4 0 0 0.00 0 0 0 0 0  
## p\_co\_5 0 0 0.00 0 0 0 0 0  
## p\_co\_6 0 0 0.00 0 0 0 0 0  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 30.96 0 0 0 0 0  
## s\_b 0 1 0.00 0 0 0 0 0  
## p\_co\_1 0 0 0.00 0 0 0 0 0  
## p\_co\_2 0 0 0.00 0 0 0 0 0  
## p\_co\_3 0 0 0.00 0 0 0 0 0  
## p\_co\_4 0 0 0.00 0 0 0 0 0  
## p\_co\_5 0 0 0.00 0 0 0 0 0  
## p\_co\_6 0 0 0.00 0 0 0 0 0

Scenario 2: 2018

## $A4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 460.33 14.67 1 13.25 1.25 4.25  
## s\_b 0 1 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0 0.00 0.00 0.00  
##   
## $A4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 10.67 8.25 9.25 2.5 0.5 1.25  
## s\_b 0 1 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.0 0.0 0.00  
##   
## $C2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 36077.33 15592.33 6958.8 6298.6 2192.13 272  
## s\_b 0 1 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_1 0 0 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_2 0 0 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_3 0 0 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_4 0 0 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_5 0 0 0.00 0.00 0.0 0.0 0.00 0  
## p\_co\_6 0 0 0.00 0.00 0.0 0.0 0.00 0  
##   
## $C2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 84140.39 3127.22 897.67 506.33 224.17 34.83  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 21662.67 7965.78 3138.78 166.33 271.33 75.25  
## s\_b 0 1 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0.00 0.00 0.00  
##   
## $C3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 292.33 517.33 207.25 144 35.5 51.25  
## s\_b 0 1 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_1 0 0 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_2 0 0 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_3 0 0 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_4 0 0 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_5 0 0 0.00 0.00 0.00 0 0.0 0.00  
## p\_co\_6 0 0 0.00 0.00 0.00 0 0.0 0.00  
##   
## $C4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 93672.33 7124 18026.33 722 500.67 272.67  
## s\_b 0 1 0.00 0 0.00 0 0.00 0.00  
## p\_co\_1 0 0 0.00 0 0.00 0 0.00 0.00  
## p\_co\_2 0 0 0.00 0 0.00 0 0.00 0.00  
## p\_co\_3 0 0 0.00 0 0.00 0 0.00 0.00  
## p\_co\_4 0 0 0.00 0 0.00 0 0.00 0.00  
## p\_co\_5 0 0 0.00 0 0.00 0 0.00 0.00  
## p\_co\_6 0 0 0.00 0 0.00 0 0.00 0.00  
##   
## $C4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 6139.56 2349 830.5 164.75 52.25 18.75  
## s\_b 0 1 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0 0.0 0.00 0.00 0.00  
##   
## $O3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 3353.67 849.25 424.75 218 123.25 79.6  
## s\_b 0 1 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_1 0 0 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_2 0 0 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_3 0 0 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_4 0 0 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_5 0 0 0.00 0.00 0.00 0 0.00 0.0  
## p\_co\_6 0 0 0.00 0.00 0.00 0 0.00 0.0  
##   
## $O3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 658 236.6 307.8 205.6 161.2 105  
## s\_b 0 1 0 0.0 0.0 0.0 0.0 0  
## p\_co\_1 0 0 0 0.0 0.0 0.0 0.0 0  
## p\_co\_2 0 0 0 0.0 0.0 0.0 0.0 0  
## p\_co\_3 0 0 0 0.0 0.0 0.0 0.0 0  
## p\_co\_4 0 0 0 0.0 0.0 0.0 0.0 0  
## p\_co\_5 0 0 0 0.0 0.0 0.0 0.0 0  
## p\_co\_6 0 0 0 0.0 0.0 0.0 0.0 0  
##   
## $O4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 3696.56 1021 267 227 363 65.25  
## s\_b 0 1 0.00 0 0 0 0 0.00  
## p\_co\_1 0 0 0.00 0 0 0 0 0.00  
## p\_co\_2 0 0 0.00 0 0 0 0 0.00  
## p\_co\_3 0 0 0.00 0 0 0 0 0.00  
## p\_co\_4 0 0 0.00 0 0 0 0 0.00  
## p\_co\_5 0 0 0.00 0 0 0 0 0.00  
## p\_co\_6 0 0 0.00 0 0 0 0 0.00  
##   
## $O4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 3361.56 2109.44 891.5 722.5 432.25 154.75  
## s\_b 0 1 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_1 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_2 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_3 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_4 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_5 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
## p\_co\_6 0 0 0.00 0.00 0.0 0.0 0.00 0.00  
##   
## $S2\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 47226.33 36547 24963.5 18982.89 6499.89 1756.22  
## s\_b 0 1 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_1 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_2 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_3 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_4 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_5 0 0 0.00 0 0.0 0.00 0.00 0.00  
## p\_co\_6 0 0 0.00 0 0.0 0.00 0.00 0.00  
##   
## $S2\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 54736.67 78894 55179.33 21709.5 5373.67 1397.67  
## s\_b 0 1 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_1 0 0 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_2 0 0 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_3 0 0 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_4 0 0 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_5 0 0 0.00 0 0.00 0.0 0.00 0.00  
## p\_co\_6 0 0 0.00 0 0.00 0.0 0.00 0.00  
##   
## $S3\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 1249255 702469.2 251112.9 62278.67 52229.92 63615.4  
## s\_b 0 1 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_1 0 0 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_2 0 0 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_3 0 0 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_4 0 0 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_5 0 0 0 0.0 0.0 0.00 0.00 0.0  
## p\_co\_6 0 0 0 0.0 0.0 0.00 0.00 0.0  
##   
## $S3\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 682268.7 163529.3 111944.6 31397.89 27976.67 5621.89  
## s\_b 0 1 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_1 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_2 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_3 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_4 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_5 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
## p\_co\_6 0 0 0.0 0.0 0.0 0.00 0.00 0.00  
##   
## $S4\_conv  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 287288.8 101940.4 38300.5 7487.5 5401.83 18928.92  
## s\_b 0 1 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_1 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_2 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_3 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_4 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_5 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
## p\_co\_6 0 0 0.0 0.0 0.0 0.0 0.00 0.00  
##   
## $S4\_low  
## s\_t s\_b p\_co\_1 p\_co\_2 p\_co\_3 p\_co\_4 p\_co\_5 p\_co\_6  
## s\_t 1 0 41160 14720 25259 18228 6427.83 4673.56  
## s\_b 0 1 0 0 0 0 0.00 0.00  
## p\_co\_1 0 0 0 0 0 0 0.00 0.00  
## p\_co\_2 0 0 0 0 0 0 0.00 0.00  
## p\_co\_3 0 0 0 0 0 0 0.00 0.00  
## p\_co\_4 0 0 0 0 0 0 0.00 0.00  
## p\_co\_5 0 0 0 0 0 0 0.00 0.00  
## p\_co\_6 0 0 0 0 0 0 0.00 0.00

### C - Simulation

#### Seed production threshold

We pooled all the data points in Nguyen and Liebman (2022a) into one regression of ln(individual fecundity +1) against ln(individual aboveground mass + 0.005) and estimated twenty-four means of fecundity on natural logarithm scales using emmeans(model, ~ Biomass, at = list(Biomass = c(). The values in Biomass = c() were the means of 24 quantiles of individual plant size on the original scale (gram/individual).

Table A5: Mean on the original scale (M) and mean (m) and standard deviation (s) on natural logarithm scale estimation from a set of mean aboveground mass values. m and s were used to assign the mean and standard deviation values in the rlnorm function in the simulation.

| Aboveground mass | M | m | SE\_ln\_Seed | s |
| --- | --- | --- | --- | --- |
| 0.04 | 13.58 | 2.66 | 0.21 | 0.89 |
| 0.09 | 30.84 | 3.44 | 0.18 | 0.76 |
| 0.14 | 46.55 | 3.85 | 0.17 | 0.70 |
| 0.21 | 67.56 | 4.22 | 0.16 | 0.65 |
| 0.28 | 91.73 | 4.52 | 0.15 | 0.61 |
| 0.38 | 122.33 | 4.81 | 0.14 | 0.56 |
| 0.48 | 155.93 | 5.05 | 0.13 | 0.53 |
| 0.56 | 182.74 | 5.21 | 0.13 | 0.51 |
| 0.64 | 208.18 | 5.34 | 0.12 | 0.50 |
| 0.79 | 257.03 | 5.55 | 0.12 | 0.48 |
| 0.97 | 316.83 | 5.75 | 0.12 | 0.46 |
| 1.23 | 403.27 | 6.00 | 0.11 | 0.45 |
| 1.65 | 542.18 | 6.29 | 0.11 | 0.44 |
| 2.30 | 757.22 | 6.63 | 0.11 | 0.43 |
| 3.16 | 1,040.21 | 6.94 | 0.11 | 0.43 |
| 4.69 | 1,552.89 | 7.34 | 0.11 | 0.44 |
| 6.63 | 2,204.30 | 7.69 | 0.12 | 0.46 |
| 8.92 | 2,975.76 | 7.99 | 0.12 | 0.48 |
| 13.50 | 4,529.40 | 8.41 | 0.13 | 0.52 |
| 21.21 | 7,163.44 | 8.87 | 0.14 | 0.58 |
| 32.94 | 11,200.58 | 9.31 | 0.16 | 0.63 |
| 54.32 | 18,619.89 | 9.82 | 0.18 | 0.70 |
| 123.01 | 42,785.63 | 10.64 | 0.21 | 0.83 |
| 669.01 | 240,902.15 | 12.35 | 0.28 | 1.11 |

The data in the model projection (Appendix B) was used in this simulation. 100 iterations of simulation were run per each rotation crossed with corn weed management regime. The full simulation algorithm is detailed below.

# event sequence: seed dropped - tillage - overwinter - tillage - emerge - survive - new seed  
  
# create a function   
# vec: starting seed column  
# poh: post-harvest tillage  
# ow: over winter seed survival  
# prt: pre-planting-tillage  
# em: emergence  
# sv: seed survival rate and seedling to maturity success rate  
# seed: fecundity  
  
rot\_2year\_conv <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,  
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S){  
   
  
 seed\_C[1,3] <- rlnorm(1, 2.65, 0.89)  
 seed\_C[1,4] <- rlnorm(1, 2.65, 0.89)  
 seed\_C[1,5] <- rlnorm(1, 2.65, 0.89)   
  
  
 seed\_S[1,3] <- rlnorm(1, 2.65, 0.89)  
 seed\_S[1,4] <- rlnorm(1, 2.65, 0.89)  
 seed\_S[1,5] <- rlnorm(1, 2.65, 0.89)  
  
  
 # corn phase dynamics   
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec   
# soybean phase dynamics  
  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn   
  
 after\_soy  
}  
  
rot\_2year\_low <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,  
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S){  
   
  
 seed\_C[1,3] <- rlnorm(1, 4.81, 0.56)  
 seed\_C[1,4] <- rlnorm(1, 4.81, 0.56)  
 seed\_C[1,5] <- rlnorm(1, 4.81, 0.56)  
  
  
 seed\_S[1,3] <- rlnorm(1, 4.81, 0.56)  
 seed\_S[1,4] <- rlnorm(1, 4.81, 0.56)  
 seed\_S[1,5] <- rlnorm(1, 4.81, 0.56)  
  
 # corn phase dynamics   
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec   
# soybean phase dynamics  
  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn   
  
 after\_soy  
}

##### with corn under conventional weed management {-}  
t <- 100  
N\_2yr\_conv <- list() # blank data frame to save loop output   
N\_2yr\_conv[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_2yr\_conv[[i]] = rot\_2year\_conv(vec = N\_2yr\_conv[[i-1]],  
 poh\_C = fall\_tillage$C2\_conv,  
 ow\_C = overwinter$C2\_conv,  
 prt\_C = spring\_tillage$C2\_conv,  
 em\_C = emergence$C2\_conv,  
 sv\_C = summer\_survival$C2\_conv,  
 seed\_C = fecundity18$C2\_conv,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S2\_conv,  
 ow\_S = overwinter$S2\_conv,  
 prt\_S = spring\_tillage$S2\_conv,  
 em\_S = emergence$S2\_conv,  
 sv\_S = summer\_survival$S2\_conv,  
 seed\_S = fecundity18$S2\_conv)  
}  
  
N\_2yr\_conv\_df <- N\_2yr\_conv %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_3", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "2-year",  
 Corn\_weed\_management = "conventional") %>%  
 na.omit()

##### with corn under low herbicide weed management {-}  
N\_2yr\_low <- list() # blank dataframe to save loop output   
  
N\_2yr\_low[[1]] <- starting\_point   
for (i in 2:t) {   
 N\_2yr\_low[[i]] = rot\_2year\_low(vec = N\_2yr\_low[[i-1]],  
 poh\_C = fall\_tillage$C2\_low,  
 ow\_C = overwinter$C2\_low,  
 prt\_C = spring\_tillage$C2\_low,  
 em\_C = emergence$C2\_low,  
 sv\_C = summer\_survival$C2\_low,  
 seed\_C = fecundity18$C2\_low,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S2\_low,  
 ow\_S = overwinter$S2\_low,  
 prt\_S = spring\_tillage$S2\_low,  
 em\_S = emergence$S2\_low,  
 sv\_S = summer\_survival$S2\_low,  
 seed\_S = fecundity18$S2\_low)  
}  
  
N\_2yr\_low\_df <- N\_2yr\_low %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_3", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "2-year",  
 Corn\_weed\_management = "low") %>%  
 na.omit()

rot\_3year\_conv <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,   
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S ,  
 poh\_O, ow\_O, prt\_O, em\_O, sv\_O, seed\_O){  
   
  
 seed\_C[1,3] <- rlnorm(1, 5.34, 0.5)  
 seed\_C[1,4] <- rlnorm(1, 5.34, 0.5)  
 seed\_C[1,5] <- rlnorm(1, 5.34, 0.5)  
  
  
 seed\_S[1,3] <- rlnorm(1, 5.34, 0.5)  
 seed\_S[1,4] <- rlnorm(1, 5.34, 0.5)  
 seed\_S[1,5] <- rlnorm(1, 5.34, 0.5)  
  
# corn phase dynamics   
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec   
 # soybean phase dynamics  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn  
# oat phase dynamics  
 after\_oat <- seed\_O %\*% sv\_O %\*% em\_O %\*% prt\_O %\*% ow\_O %\*% poh\_O %\*% after\_soy   
   
 after\_oat  
}  
  
### low herbicide weed management  
  
rot\_3year\_low <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,   
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S ,  
 poh\_O, ow\_O, prt\_O, em\_O, sv\_O, seed\_O){  
   
  
 seed\_C[1,3] <- rlnorm(1, 5.34, 0.5)  
# seed\_C[1,3] <- rlnorm(1, 2.65, 0.89)  
 seed\_C[1,4] <- rlnorm(1, 5.34, 0.5)  
# seed\_C[1,4] <- rlnorm(1, 2.65, 0.89)  
 seed\_C[1,5] <- rlnorm(1, 5.34, 0.5)  
  
  
 seed\_S[1,3] <- rlnorm(1, 5.34, 0.5)  
# seed\_S[1,3] <- rlnorm(1, 2.65, 0.89)  
 seed\_S[1,4] <- rlnorm(1, 5.34, 0.5)  
# seed\_S[1,4] <- rlnorm(1, 2.65, 0.89)  
 seed\_S[1,5] <- rlnorm(1, 5.34, 0.5)  
  
# corn phase dynamics   
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec   
 # soybean phase dynamics  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn  
# oat phase dynamics  
 after\_oat <- seed\_O %\*% sv\_O %\*% em\_O %\*% prt\_O %\*% ow\_O %\*% poh\_O %\*% after\_soy   
   
 after\_oat  
}

##### with corn under conventional weed management {-}  
N\_3yr\_conv <- list() # blank dataframe to save loop output   
  
N\_3yr\_conv[[1]] <- starting\_point   
  
  
for (i in 2:t) {   
 N\_3yr\_conv[[i]] = rot\_3year\_conv(vec = N\_3yr\_conv[[i-1]],  
 poh\_C = fall\_tillage$C3\_conv,  
 ow\_C = overwinter$C3\_conv,  
 prt\_C = spring\_tillage$C3\_conv,  
 em\_C = emergence$C3\_conv,  
 sv\_C = summer\_survival$C3\_conv,  
 seed\_C = fecundity18$C3\_conv,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S3\_conv,  
 ow\_S = overwinter$S3\_conv,  
 prt\_S = spring\_tillage$S3\_conv,  
 em\_S = emergence$S3\_conv,  
 sv\_S = summer\_survival$S3\_conv,  
 seed\_S = fecundity18$S3\_conv,  
   
 #oat dynamics   
 poh\_O = fall\_tillage$O3\_conv,  
 ow\_O = overwinter$O3\_conv,  
 prt\_O = spring\_tillage$O3\_conv,  
 em\_O = emergence$O3\_conv,  
 sv\_O = summer\_survival$O3\_conv,  
 seed\_O = fecundity18$O3\_conv)  
}  
  
N\_3yr\_conv\_df <- N\_3yr\_conv %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_3", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = nthroot(lambda\_cycle,3),  
 Rotation = "3-year",  
 Corn\_weed\_management = "conventional") %>%  
 na.omit()

##### with corn under low herbicide weed management {-}   
N\_3yr\_low <- list() # blank dataframe to save loop output   
  
N\_3yr\_low[[1]] <- starting\_point   
  
  
for (i in 2:t) {   
 N\_3yr\_low[[i]] = rot\_3year\_low(vec = N\_3yr\_low[[i-1]],  
 poh\_C = fall\_tillage$C3\_conv,  
 ow\_C = overwinter$C3\_low,  
 prt\_C = spring\_tillage$C3\_low,  
 em\_C = emergence$C3\_low,  
 sv\_C = summer\_survival$C3\_low,  
 seed\_C = fecundity18$C3\_low,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S3\_low,  
 ow\_S = overwinter$S3\_low,  
 prt\_S = spring\_tillage$S3\_low,  
 em\_S = emergence$S3\_low,  
 sv\_S = summer\_survival$S3\_low,  
 seed\_S = fecundity18$S3\_low,  
   
 #oat dynamics   
 poh\_O = fall\_tillage$O3\_low,  
 ow\_O = overwinter$O3\_low,  
 prt\_O = spring\_tillage$O3\_low,  
 em\_O = emergence$O3\_low,  
 sv\_O = summer\_survival$O3\_low,  
 seed\_O = fecundity18$O3\_low)  
}  
  
N\_3yr\_low\_df <- N\_3yr\_low %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_3", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = nthroot(lambda\_cycle,3),  
 Rotation = "3-year",  
 Corn\_weed\_management = "low") %>%  
 na.omit()

### conventional weed management  
rot\_4year\_conv <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,   
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S ,  
 poh\_O, ow\_O, prt\_O, em\_O, sv\_O, seed\_O,  
 poh\_A, ow\_A, prt\_A, em\_A, sv\_A, seed\_A){  
   
 seed\_C[1,3] <- rlnorm(1, 7.34, 0.44)  
 seed\_C[1,4] <- rlnorm(1, 5.75, 0.46)  
 seed\_C[1,5] <- rlnorm(1, 5.75, 0.46)  
  
  
 seed\_S[1,3] <- rlnorm(1, 7.34, 0.44)  
 seed\_S[1,4] <- rlnorm(1, 5.75, 0.46)  
 seed\_S[1,5] <- rlnorm(1, 5.75, 0.46)  
  
# corn phase dynamics  
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec  
# soybean phase dynamics  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn  
# oat phase dynamics  
after\_oat <- seed\_O %\*% sv\_O %\*% em\_O %\*% prt\_O %\*% ow\_O %\*% poh\_O %\*% after\_soy   
# alfalfa phase dynamics  
after\_alfalfa <- seed\_A %\*% sv\_A %\*% em\_A %\*% prt\_A %\*% ow\_A %\*% poh\_A %\*% after\_oat   
   
 after\_alfalfa  
}  
  
### low herbicide weed management  
rot\_4year\_low <- function(vec, poh\_C, ow\_C, prt\_C, em\_C, sv\_C, seed\_C,   
 poh\_S, ow\_S, prt\_S, em\_S, sv\_S, seed\_S ,  
 poh\_O, ow\_O, prt\_O, em\_O, sv\_O, seed\_O,  
 poh\_A, ow\_A, prt\_A, em\_A, sv\_A, seed\_A){  
   
 seed\_C[1,3] <- rlnorm(1, 5.75, 0.46)  
 seed\_C[1,4] <- rlnorm(1, 5.75, 0.46)  
 seed\_C[1,5] <- rlnorm(1, 5.75, 0.46)  
  
  
 seed\_S[1,3] <- rlnorm(1, 5.75, 0.46)  
 seed\_S[1,4] <- rlnorm(1, 5.75, 0.46)  
 seed\_S[1,5] <- rlnorm(1, 5.75, 0.46)  
  
# corn phase dynamics  
 after\_corn <- seed\_C %\*% sv\_C %\*% em\_C %\*% prt\_C %\*% ow\_C %\*% poh\_C %\*% vec  
# soybean phase dynamics  
 after\_soy <- seed\_S %\*% sv\_S %\*% em\_S %\*% prt\_S %\*% ow\_S %\*% poh\_S %\*% after\_corn  
# oat phase dynamics  
after\_oat <- seed\_O %\*% sv\_O %\*% em\_O %\*% prt\_O %\*% ow\_O %\*% poh\_O %\*% after\_soy   
# alfalfa phase dynamics  
after\_alfalfa <- seed\_A %\*% sv\_A %\*% em\_A %\*% prt\_A %\*% ow\_A %\*% poh\_A %\*% after\_oat   
   
 after\_alfalfa  
}

##### with corn under conventional weed management {-}  
N\_4yr\_conv <- list() # blank dataframe to save loop output   
  
N\_4yr\_conv[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_4yr\_conv[[i]] = rot\_4year\_conv(vec = N\_4yr\_conv[[i-1]],  
 poh\_C = fall\_tillage$C4\_conv,  
 ow\_C = overwinter$C4\_conv,  
 prt\_C = spring\_tillage$C4\_conv,  
 em\_C = emergence$C4\_conv,  
 sv\_C = summer\_survival$C4\_conv,  
 seed\_C = fecundity18$C4\_conv,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S4\_conv,  
 ow\_S = overwinter$S4\_conv,  
 prt\_S = spring\_tillage$S4\_conv,  
 em\_S = emergence$S4\_conv,  
 sv\_S = summer\_survival$S4\_conv,  
 seed\_S = fecundity18$S4\_conv,  
   
 #oat dynamics   
 poh\_O = fall\_tillage$O4\_conv,  
 ow\_O = overwinter$O4\_conv,  
 prt\_O = spring\_tillage$O4\_conv,  
 em\_O = emergence$O4\_conv,  
 sv\_O = summer\_survival$O4\_conv,  
 seed\_O = fecundity18$O4\_conv,  
   
 #alfalfa dynamics   
 poh\_A = fall\_tillage$A4\_conv,  
 ow\_A = overwinter$A4\_conv,  
 prt\_A = spring\_tillage$A4\_conv,  
 em\_A = emergence$A4\_conv,  
 sv\_A = summer\_survival$A4\_conv,  
 seed\_A = fecundity18$A4\_conv)  
}  
  
N\_4yr\_conv\_df <- N\_4yr\_conv %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_4", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = nthroot(lambda\_cycle,4),  
 Rotation = "4-year",  
 Corn\_weed\_management = "conventional") %>%  
 na.omit()

##### with corn under low herbicide weed management {-}   
N\_4yr\_low <- list() # blank dataframe to save loop output   
  
N\_4yr\_low[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_4yr\_low[[i]] = rot\_4year\_low(vec = N\_4yr\_low[[i-1]],  
 poh\_C = fall\_tillage$C4\_low,  
 ow\_C = overwinter$C4\_low,  
 prt\_C = spring\_tillage$C4\_low,  
 em\_C = emergence$C4\_low,  
 sv\_C = summer\_survival$C4\_low,  
 seed\_C = fecundity18$C4\_low,  
   
 #soybean dynamics   
 poh\_S = fall\_tillage$S4\_low,  
 ow\_S = overwinter$S4\_low,  
 prt\_S = spring\_tillage$S4\_low,  
 em\_S = emergence$S4\_low,  
 sv\_S = summer\_survival$S4\_low,  
 seed\_S = fecundity18$S4\_low,  
   
 #oat dynamics   
 poh\_O = fall\_tillage$O4\_low,  
 ow\_O = overwinter$O4\_low,  
 prt\_O = spring\_tillage$O4\_low,  
 em\_O = emergence$O4\_low,  
 sv\_O = summer\_survival$O4\_low,  
 seed\_O = fecundity18$O4\_low,  
   
 #alfalfa dynamics   
 poh\_A = fall\_tillage$A4\_low,  
 ow\_A = overwinter$A4\_low,  
 prt\_A = spring\_tillage$A4\_low,  
 em\_A = emergence$A4\_low,  
 sv\_A = summer\_survival$A4\_low,  
 seed\_A = fecundity18$A4\_low)  
}  
  
N\_4yr\_low\_df <- N\_4yr\_low %>%   
 unlist(recursive = FALSE) %>%  
 data.frame() %>%  
 dplyr::rename(counts = ".") %>%  
 dplyr::mutate(category = rep(c("top", "bottom", "cohort\_1", "cohort\_2", "cohort\_4", "cohort\_4", "cohort\_5", "cohort\_6"),t)) %>%  
 filter(category %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = rep(1:t, each = 2)) %>%  
 group\_by(category) %>%  
 mutate(lambda\_cycle = counts/lag(counts),  
 lambda\_annualized = nthroot(lambda\_cycle,4),  
 Rotation = "4-year",  
 Corn\_weed\_management = "low") %>%  
 na.omit()

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