# Results and discussion

## Waterhemp population growth rates

### Scenario 1

Using 2019 fecundity rates, that were estimated from individual plant size using eighteen equations from Nguyen and Liebman (2022), waterhemp population densities were decreasing in all rotations, the fastest in the 2-year rotation under low herbicide corn weed management and the 3-year rotation under both corn weed management programs (Figures 1). ’s decreased right after the first phase in the 2-year (C2) and 3-year (C3) rotations, but increased in the first phase of the 4-year rotation (C4).

### Scenario 2

*In scenario 2, plant cohorts were assigned by their size, under the assumption that plant size decreases as emergence delays (Table).* Using 2018 fecundity rates, waterhemp population densities were increasing rapidly in all rotations, the fastest in the 2-year rotation (Figures 2). The population increase in the 3-year rotation under low herbicide corn weed management was similar to those of the 4-year rotation. Even though the populations were all increasing, the partition of seedbanks differed between rotations and consistent between two corn weed management regimes within the same rotation. In the 2-year rotation, a large portion of the seedbanks were at the 0-2 cm; 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 seedbanks were at the bottom stratum.

A noteworthy observation is that the oat phase in the 3-year rotation (O3) alfalfa phase in the 4-year rotation (A4) offered an opportunity for decreasing , which was not possible in any other crop phases in the three examined rotations. However, the decline in in O3 () and A4 () were not strong enough to deplete the replenishment from the corn ( and ) and soybean ( and ) phases. It would be useful to examine how many years of continuous overwinter cover crops is necessary and which cool-season crop species would be efficient in decreasing waterhemp after steady seedbank replenishment.

## Elasticities of popilation growth rates to lower-level demographic parameters

### Scenario 2

Elasticity of ’s to fecundity rates, as a group, were ranked first in all crop phases; but the specific influence of each cohort’s fecundity differed by crop phase. The elasticity of ’s elasticity to cohort one fecundity were the highest in 2-year rotation corn (C2), 3-year rotation soybean (S3), and 4-year rotation oat (O4) phases. The elasticity of ’s elasticity to cohort two fecundity were the highest in 2-year rotation soybean (S2), 3-year rotation corn (C3) and oat (O4), and 4-year rotation corn (C4), soybean (S4), and alfalfa (A4) phases. The second-ranked group of demographic parameters to differed by rotation and crop phase. In the 2-year rotation, the second-ranked group of parameters in contribution to elasticity of were both pre-planting tillage-induced seed movement and overwinter seed survival. In the 3-year rotation, the second-ranked group of parameters in contribution to elasticity of was pre-planting tillage-induced seed movement in the warm-season crop phases; and overwinter seed survival in the cool-season crop phase. In the 4-year rotation, the second-ranked group of parameters in contribution to elasticity of was overwinter seed survival in the cool-season crop phase; and pre-planting tillage-induced seed movement in the warm-season crop phases; a reverse trend as compared to the 3-year rotation’s dynamics.

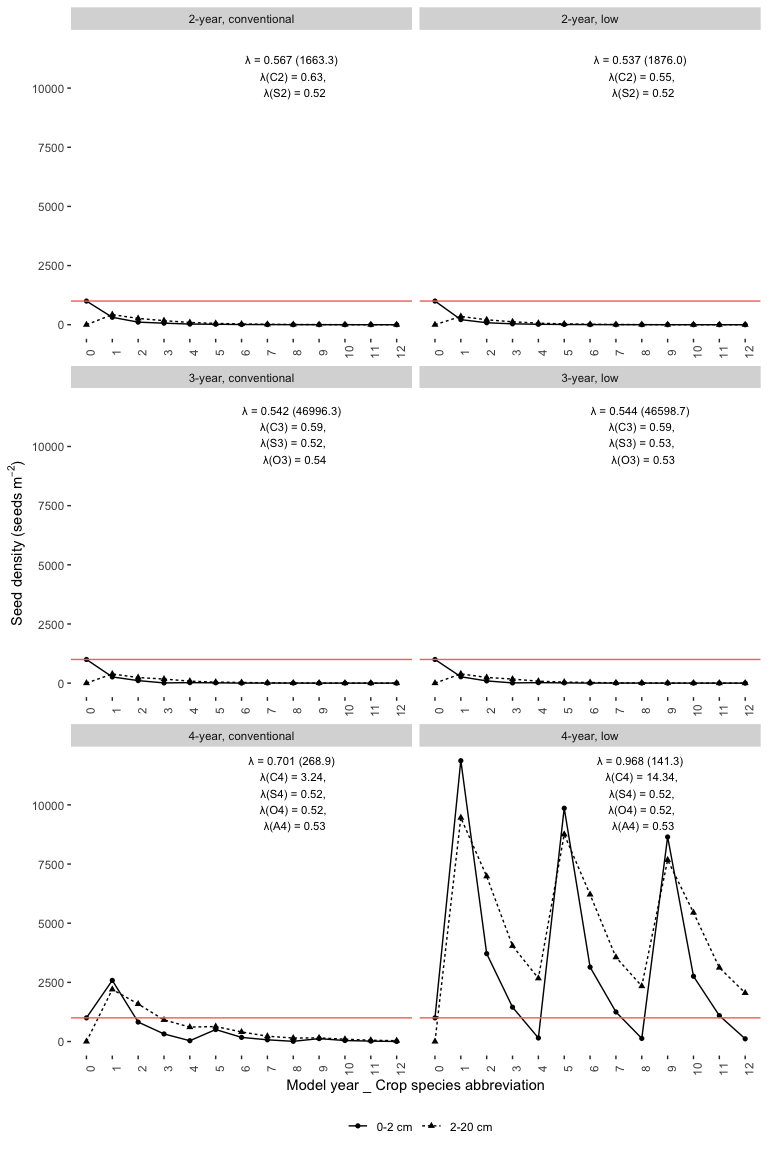


Figure 1: Scenario 1: Changes of a seed column after twelve model years in three rotations (2-year, 3-year, and 4-year) crossed with two corn weed management programs (conventional and low herbicide). The model started at year 0 with 1000 and 0 seeds per squared meter at the top (0-2 cm) and bottom (2-20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

Table 1: Scenario1 - Elasticity of population growth rates in three rotations crossed with two corn weed management programs to lower-level demographic parameters

| Crop\_ID | Corn\_weed\_management | st1\_1\* | st2\_1\* | st1\_2\* | st2\_2\* | 1-sum(e)§ | sss\_1† | sss\_2† | f\_1⁋ | f\_2⁋ | f\_3⁋ | f\_4⁋ | f\_5⁋ | f\_6⁋ | ft1\_1⌇ | ft2\_1⌇ | ft1\_2⌇ | ft2\_2⌇ | wss\_1⍑ | wss\_2⍑ |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| C2 | conventional | 0.15 | 0.23 | 0.46 | 0.72 | 0.13 | 0.08 | 0.30 | **43.13** | 10.71 | 2.86 | 0.92 | 0.48 | 0.62 | 0.09 | 0.18 | 0.26 | 0.52 | 0.08 | 0.31 |
| C2 | low | 0.15 | 0.24 | 0.48 | 0.76 | 0.14 | 0.09 | 0.31 | **3.15** | 0.78 | 0.21 | 0.07 | 0.03 | 0.05 | 0.09 | 0.19 | 0.27 | 0.54 | 0.09 | 0.32 |
| S2 | conventional | 0.14 | 0.24 | 0.41 | 0.70 | 0.15 | 0.07 | 0.28 | 0.12 | **0.75** | 0.05 | 0.03 | 0.03 | 0.03 | 0.10 | 0.12 | 0.31 | 0.37 | 0.10 | 0.28 |
| S2 | low | 0.15 | 0.26 | 0.43 | 0.73 | 0.16 | 0.08 | 0.29 | 0.69 | **4.18** | 0.27 | 0.20 | 0.16 | 0.15 | 0.11 | 0.13 | 0.33 | 0.39 | 0.10 | 0.30 |
| C3 | conventional | 0.01 | 0.07 | 0.23 | **1.10** | 0.07 | 0.04 | 0.42 | 0.56 | 1.00 | 0.65 | 0.42 | 0.05 | 0.02 | 0.05 | 0.18 | 0.16 | 0.55 | 0.05 | 0.51 |
| C3 | low | 0.01 | 0.07 | 0.23 | **1.10** | 0.07 | 0.04 | 0.42 | 0.46 | 0.83 | 0.54 | 0.35 | 0.04 | 0.01 | 0.05 | 0.18 | 0.17 | 0.55 | 0.05 | 0.51 |
| S3 | conventional | 0.10 | 0.26 | 0.33 | 0.88 | 0.06 | 0.03 | 0.46 | **0.91** | 0.18 | 0.04 | 0.00 | 0.01 | 0.02 | 0.06 | 0.19 | 0.19 | 0.60 | 0.03 | 0.52 |
| S3 | low | 0.10 | 0.26 | 0.33 | **0.89** | 0.07 | 0.03 | 0.47 | 0.83 | 0.16 | 0.04 | 0.00 | 0.01 | 0.01 | 0.06 | 0.19 | 0.19 | 0.60 | 0.03 | 0.52 |
| O3 | conventional | 0.08 | 0.24 | 0.28 | **0.87** | 0.06 | 0.01 | 0.45 | 0.05 | 0.25 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.17 | 0.05 | 0.80 | 0.00 | 0.67 |
| O3 | low | 0.08 | 0.24 | 0.29 | **0.88** | 0.06 | 0.01 | 0.46 | 0.06 | 0.30 | 0.02 | 0.03 | 0.01 | 0.01 | 0.01 | 0.17 | 0.05 | 0.80 | 0.00 | 0.68 |
| C4 | conventional | 0.02 | 0.04 | 0.36 | 0.66 | 0.07 | 0.04 | 0.25 | 136.57 | **305.24** | 4.09 | 231.70 | 12.63 | 4.57 | 0.05 | 0.13 | 0.15 | 0.37 | 0.05 | 0.23 |
| C4 | low | 0.02 | 0.03 | 0.26 | 0.48 | 0.05 | 0.03 | 0.18 | 144.55 | **323.07** | 4.33 | 245.23 | 13.36 | 4.83 | 0.04 | 0.09 | 0.11 | 0.27 | 0.03 | 0.17 |
| S4 | conventional | 0.11 | 0.19 | 0.27 | 0.50 | 0.09 | 0.07 | 0.22 | 0.42 | 1.07 | 0.75 | 0.46 | 0.21 | 0.08 | 0.10 | 0.12 | 0.23 | 0.29 | **3.32** | 0.20 |
| S4 | low | 0.08 | 0.14 | 0.20 | 0.36 | 0.06 | 0.05 | 0.16 | 0.27 | 0.68 | 0.47 | 0.29 | 0.13 | 0.05 | 0.07 | 0.09 | 0.17 | 0.21 | **2.41** | 0.15 |
| O4 | conventional | 2.97 | 3.01 | 5.41 | **5.49** | 2.76 | 0.63 | 1.44 | 2.55 | 0.74 | 0.29 | 0.16 | 0.16 | 0.20 | 1.03 | 1.24 | 1.69 | 2.05 | 0.80 | 1.16 |
| O4 | low | 2.15 | 2.18 | 3.92 | **3.98** | 2.00 | 0.46 | 1.04 | 2.88 | 0.83 | 0.33 | 0.18 | 0.18 | 0.22 | 0.74 | 0.90 | 1.23 | 1.49 | 0.58 | 0.84 |
| A4 | conventional | 1.92 | 2.56 | 1.63 | 2.18 | 1.59 | 0.03 | 0.25 | 7.09 | **36.78** | 2.14 | 1.67 | 1.39 | 1.35 | 0.01 | 0.11 | 0.03 | 0.54 | 0.01 | 0.28 |
| A4 | low | 1.39 | 1.86 | 1.19 | 1.58 | 1.18 | 0.02 | 0.18 | 2.79 | **14.49** | 0.84 | 0.66 | 0.55 | 0.53 | 0.00 | 0.08 | 0.02 | 0.39 | 0.01 | 0.20 |
| \*st\_ij: the probability of seed movement from soil stratum i to j by pre-planting tillage | | | | | | | | | | | | | | | | | | | | |
| §1-sum(e): the probability of non-emerging seeds in the top (0-2 cm) soil stratum | | | | | | | | | | | | | | | | | | | | |
| †sss\_1 and sss\_2: the summer survival probabilities of the seeds in the top (0-2 cm) and bottom (2-20 cm) soil strata | | | | | | | | | | | | | | | | | | | | |
| ⁋f\_1 though f\_6: the individual fecundity of mature plants in cohorts 1 through 6 | | | | | | | | | | | | | | | | | | | | |
| ⌇ft\_ij: the probability of seed movement from soil stratum i to j by post-harvest tillage | | | | | | | | | | | | | | | | | | | | |
| ⍑wss\_1 and wss\_2: the overwinter survival probabilities of seeds in the top (0-2 cm) and bottom (2-20 cm) soil strata | | | | | | | | | | | | | | | | | | | | |
| All-zero columns are excluded. In Crop\_ID: C2 - corn in the 2 year rotation, S2 - soybean in the 2-year rotation, C3 - corn in the 3-year rotation, S3 - soybean in the 3-year rotation, O3 - oat intercroped with red clover in the 3-year rotation, C4 - corn in the 4-year rotation, S4 - soybean in the 4-year rotation, O4 - oat intercropped with alfalfa in the 4-year rotation, and A4 - alfalfa in the 4-year rotation. | | | | | | | | | | | | | | | | | | | | |

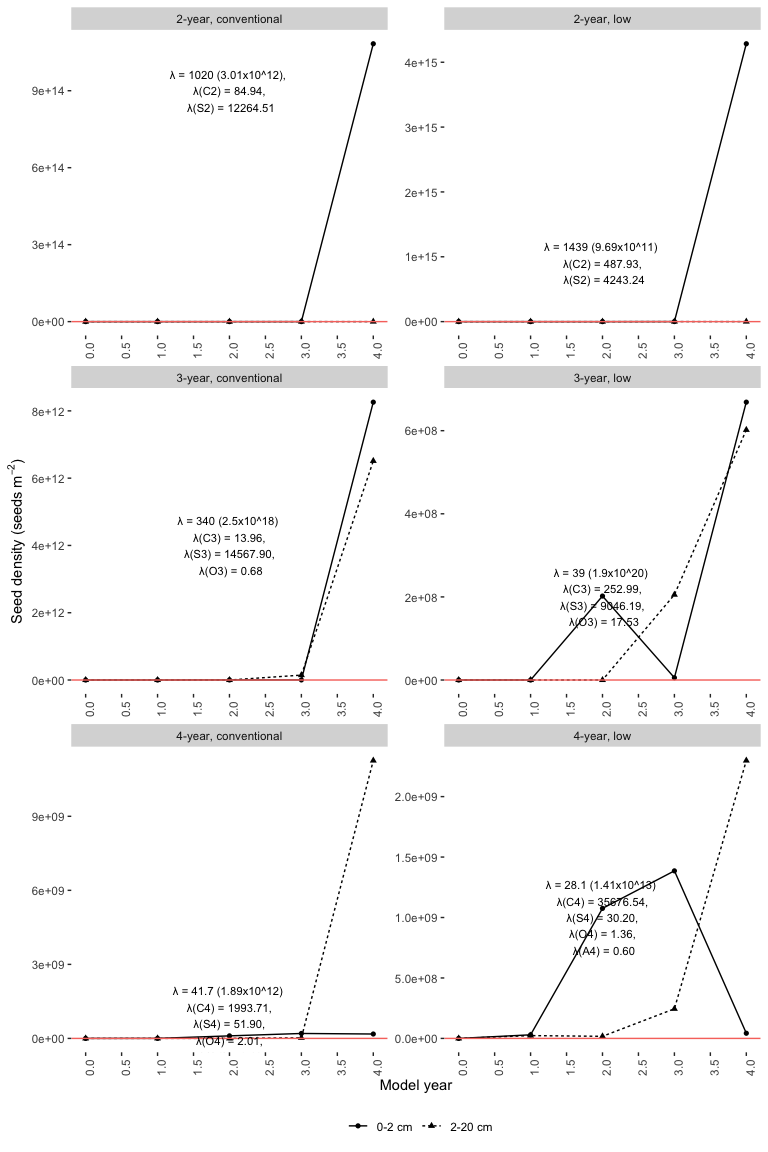


Figure 2: Scenario 1: Changes of a seed column after four model years (only four years are illustrated because of scales) in three rotations (2-year, 3-year, and 4-year) crossed with two corn weed management programs (conventional and low herbicide). The model started at year 0 with 1000 and 0 seeds per squared meter at the top (0-2 cm) and bottom (2-20 cm) strata, respectively. The red horizontal line shows the number of seeds at the top stratum at the begining of the model clock.

Table 2: Scenario 2 - Elasticity of population growth rates in three rotations crossed with two corn weed management programs to lower-level demographic parameters

| Crop\_ID | Corn\_weed\_management | st1\_1\* | st2\_1\* | st1\_2\* | st2\_2\* | 1-sum(e)§ | sss\_1† | sss\_2† | f\_1⁋ | f\_2⁋ | f\_3⁋ | f\_4⁋ | f\_5⁋ | f\_6⁋ | ft1\_1⌇ | ft2\_1⌇ | ft1\_2⌇ | ft2\_2⌇ | wss\_1⍑ | wss\_2⍑ |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| C2 | conv | 1,466.84 | 1,437.21 | 0.12 | 0.11 | 1,522.79 | 0.05 | 0.02 | **4,099,185,668.80** | 990,125,323 | 237,420,871.69 | 50,445,968.31 | 22,152,907.95 | 28,440,558.71 | 0.04 | 0.05 | 0.07 | 0.08 | 1,407.87 | 0.02 |
| C2 | low | 1,040.05 | 1,019.03 | 0.08 | 0.08 | 1,075.11 | 0.03 | 0.02 | **2,766,736,655.89** | 668,282,983 | 160,246,712.80 | 34,048,399.11 | 14,952,058.14 | 19,195,894.66 | 0.03 | 0.04 | 0.05 | 0.05 | 998.23 | 0.01 |
| S2 | conv | 1,224.96 | 1,199.30 | 855.64 | 837.72 | 2,092.52 | 0.99 | 0.43 | 2,093,885,714.17 | **14,238,156,534** | 711,346,410.36 | 517,111,697.67 | 414,505,814.44 | 395,211,907.50 | 1.47 | 0.83 | 1.00 | 0.57 | 1,684.99 | 0.00 |
| S2 | low | 868.54 | 850.35 | 606.68 | 593.98 | 1,513.48 | 0.70 | 0.30 | 1,228,712,929.01 | **8,355,091,637** | 417,425,137.15 | 303,446,279.03 | 243,236,127.89 | 231,914,271.71 | 1.04 | 0.59 | 0.71 | 0.40 | 1,194.72 | 0.00 |
| C3 | conv | 12.64 | 67.32 | 687.06 | 3,659.78 | 1,052.30 | 0.03 | 0.02 | 5,592,860,407.22 | **10,241,029,161** | 6,553,794,288.93 | 4,170,959,828.12 | 274,584,905.82 | 57,989,495.69 | 4.16 | 6.44 | 2.83 | 4.39 | 4,051.81 | 0.00 |
| C3 | low | 110.13 | 586.62 | 5,987.41 | 31,893.50 | 9,066.99 | 0.29 | 0.19 | 560,845,021.29 | **1,026,957,549** | 657,206,264.75 | 418,258,616.04 | 27,535,029.69 | 5,815,113.84 | 36.23 | 56.14 | 24.67 | 38.24 | 35,309.85 | 0.00 |
| S3 | conv | 3,560.69 | 2,425.33 | 0.17 | 0.12 | 3,767.47 | 0.00 | 0.00 | **4,430,424,819.92** | 884,087,490 | 219,595,694.18 | 18,713,992.16 | 38,195,564.95 | 83,849,529.43 | 0.03 | 0.05 | 0.05 | 0.07 | 4.89 | 3.41 |
| S3 | low | 31,029.99 | 21,135.75 | 1.49 | 1.02 | 33,065.92 | 0.00 | 0.00 | **97,536,117,996.12** | 19,463,249,057 | 4,834,414,849.40 | 411,989,870.50 | 840,878,083.09 | 1,845,953,363.11 | 0.26 | 0.40 | 0.40 | 0.60 | 42.66 | 29.74 |
| O3 | conv | 5.07 | 7.27 | 3.57 | 5.11 | 10.31 | 0.00 | 0.00 | 34,174,840.90 | **303,196,630** | 370,916.67 | 5,688,132.59 | 354,078.03 | 354,071.33 | 0.00 | 0.04 | 0.01 | 0.21 | 0.93 | 3,911.43 |
| O3 | low | 44.21 | 63.33 | 31.11 | 44.57 | 89.86 | 0.00 | 0.00 | 2,873,761.48 | **25,495,797** | 31,190.37 | 478,314.92 | 29,774.41 | 29,773.85 | 0.02 | 0.34 | 0.13 | 1.83 | 8.09 | 34,086.54 |
| C4 | conv | 0.02 | 0.02 | 1.23 | 1.21 | 1.25 | 0.01 | 0.00 | 732,440,602.93 | **1,645,017,490** | 15,670,814.43 | 1,247,105,405.17 | 61,862,197.17 | 18,259,659.49 | 0.01 | 0.01 | 0.00 | 0.00 | 1.84 | 0.00 |
| C4 | low | 0.03 | 0.03 | 1.82 | 1.79 | 1.72 | 0.01 | 0.00 | 4,514,711,997.21 | **10,139,771,288** | 96,593,790.20 | 7,687,069,384.22 | 381,314,201.65 | 112,551,247.76 | 0.02 | 0.02 | 0.00 | 0.00 | 2.74 | 0.00 |
| S4 | conv | 1.66 | 1.63 | 0.19 | 0.18 | 1.73 | 0.12 | 0.05 | 30,614,999.62 | **84,392,111** | 57,466,194.44 | 33,438,761.46 | 12,281,030.64 | 2,230,608.04 | 0.18 | 0.10 | 0.12 | 0.07 | 15,656.18 | 0.00 |
| S4 | low | 2.47 | 2.42 | 0.27 | 0.27 | 2.56 | 0.18 | 0.08 | 32,141,403.63 | **88,599,736** | 60,331,346.52 | 35,105,952.72 | 12,893,338.81 | 2,341,821.80 | 0.27 | 0.15 | 0.18 | 0.11 | 23,234.04 | 0.00 |
| O4 | conv | 13,622.02 | 13,336.57 | 127.87 | 125.19 | 12,781.83 | 18.59 | 39.29 | **8,360,399.81** | 1,850,989 | 241,204.83 | 335,121.62 | 335,121.62 | 361,855.36 | 35.22 | 43.38 | 52.93 | 65.20 | 286.31 | 34.27 |
| O4 | low | 20,215.32 | 19,791.70 | 189.75 | 185.78 | 18,968.23 | 27.58 | 58.30 | **6,486,555.88** | 1,436,120 | 187,142.80 | 260,009.71 | 260,009.71 | 280,751.53 | 52.26 | 64.38 | 78.55 | 96.76 | 424.88 | 50.85 |
| A4 | conv | 684.84 | 92.63 | 478.10 | 64.66 | 578.30 | 0.03 | 0.01 | 1,387,435.20 | **11,740,397** | 101,418.96 | 81,652.35 | 69,727.16 | 67,827.97 | 0.00 | 0.05 | 0.01 | 0.26 | 0.02 | 0.01 |
| A4 | low | 1,016.31 | 137.46 | 709.51 | 95.96 | 883.03 | 0.05 | 0.02 | 36,200.67 | **306,328** | 2,646.20 | 2,130.46 | 1,819.31 | 1,769.75 | 0.00 | 0.07 | 0.01 | 0.38 | 0.03 | 0.01 |
| \*st\_ij: the probability of seed movement from soil stratum i to j by pre-planting tillage | | | | | | | | | | | | | | | | | | | | |
| §1-sum(e): the probability of non-emerging seeds in the top (0-2 cm) soil stratum | | | | | | | | | | | | | | | | | | | | |
| †sss\_1 and sss\_2: the summer survival probabilities of the seeds in the top (0-2 cm) and bottom (2-20 cm) soil strata | | | | | | | | | | | | | | | | | | | | |
| ⁋f\_1 though f\_6: the individual fecundity of mature plants in cohorts 1 through 6 | | | | | | | | | | | | | | | | | | | | |
| ⌇ft\_ij: the probability of seed movement from soil stratum i to j by post-harvest tillage | | | | | | | | | | | | | | | | | | | | |
| ⍑wss\_1 and wss\_2: the overwinter survival probabilities of seeds in the top (0-2 cm) and bottom (2-20 cm) soil strata | | | | | | | | | | | | | | | | | | | | |
| All-zero columns are excluded. In Crop\_ID: C2 - corn in the 2 year rotation, S2 - soybean in the 2-year rotation, C3 - corn in the 3-year rotation, S3 - soybean in the 3-year rotation, O3 - oat intercroped with red clover in the 3-year rotation, C4 - corn in the 4-year rotation, S4 - soybean in the 4-year rotation, O4 - oat intercropped with alfalfa in the 4-year rotation, and A4 - alfalfa in the 4-year rotation. | | | | | | | | | | | | | | | | | | | | |

## Conclusion

Regardless of the difference in waterhemp , no crop yield decline was observed at the experiment site from 2017 through 2020 (**nguyenWeedCommunityComposition2022?**).

*This observation is consistent with waterhemp’s ability to replenish a declining soil seedbank over several years with only one successful year reported by (****davisWeedSeedPools2008?****).*

## Sensitivities and elasticities of waterhemp population growth rate to projection matrices elements

## Appendix

## Reference

Nguyen, Huong T. X., and Matt Liebman. 2022. “Impact of Cropping System Diversification on Vegetative and Reproductive Characteristics of Waterhemp (*A. Tuberculatus*).” *Frontiers in Agronomy* 4. <https://doi.org/10.3389/fagro.2022.811359>.