# event sequence: seed dropped - field cultivator - emerge - survive - new seed - chisel - overwinter   
# create a function   
# vec: starting seed column  
# prt: pre-planting-tillage  
# em: emergence  
# sv: seed survival rate and seedling to maturity success rate  
# seed: fecundity  
# poh: post-harvest tillage  
# ow: over winter seed survival  
  
##### with corn under conventional weed management {-}  
N\_2yr\_conv\_lambda <- list() # blank data frame to save loop output   
N\_2yr\_conv\_lambda[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_2yr\_conv\_lambda[[i]] = rot\_2year\_conv\_lambda(vec = N\_2yr\_conv\_lambda[[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\_lambda\_df <- N\_2yr\_conv\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",   
 "cohort\_1", "cohort\_2",   
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything()) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "2-year",  
 Corn\_weed\_management = "conventional")   
  
##### with corn under low herbicide weed management {-}  
N\_2yr\_low\_lambda <- list() # blank dataframe to save loop output   
  
N\_2yr\_low\_lambda[[1]] <- starting\_point   
for (i in 2:t) {   
 N\_2yr\_low\_lambda[[i]] = rot\_2year\_low\_lambda(vec = N\_2yr\_low\_lambda[[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\_lambda\_df <- N\_2yr\_low\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",   
 "cohort\_1", "cohort\_2",   
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything()) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "2-year",  
 Corn\_weed\_management = "low")

### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
N\_2yr\_conv\_manipulated <- rot\_2year\_conv\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_2yr\_conv\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 6)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)  
  
### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_2yr\_low\_manipulated <- rot\_2year\_low\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_2yr\_low\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 6)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_2yr\_conv\_original <- rot\_2year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_2yr\_conv\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(original\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 6)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = original\_output, names\_from = variable)  
  
### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_2yr\_low\_original <- rot\_2year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_2yr\_low\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 6)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_2yr\_conv\_all <- N\_2yr\_conv\_lambda\_df %>%  
 left\_join(N\_2yr\_conv\_manipulated\_df) %>%  
 left\_join(N\_2yr\_conv\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

N\_2yr\_low\_all <- N\_2yr\_low\_lambda\_df %>%   
 left\_join(N\_2yr\_low\_manipulated\_df) %>%  
 left\_join(N\_2yr\_low\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

##### with corn under conventional weed management {-}  
N\_3yr\_conv\_lambda <- list() # blank dataframe to save loop output   
  
N\_3yr\_conv\_lambda[[1]] <- starting\_point   
  
  
for (i in 2:t) {   
 N\_3yr\_conv\_lambda[[i]] = rot\_3year\_conv\_lambda(vec = N\_3yr\_conv\_lambda[[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\_lambda\_df <- N\_3yr\_conv\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",  
 "cohort\_1", "cohort\_2",  
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "3-year",  
 Corn\_weed\_management = "conventional")   
  
##### with corn under low herbicide weed management {-}   
N\_3yr\_low\_lambda <- list() # blank dataframe to save loop output   
  
N\_3yr\_low\_lambda[[1]] <- starting\_point   
  
  
for (i in 2:t) {   
 N\_3yr\_low\_lambda[[i]] = rot\_3year\_low\_lambda(vec = N\_3yr\_low\_lambda[[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\_lambda\_df <- N\_3yr\_low\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",  
 "cohort\_1", "cohort\_2",  
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything() ) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "3-year",  
 Corn\_weed\_management = "low")

### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
N\_3yr\_conv\_manipulated <- rot\_3year\_conv\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_3yr\_conv\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 9)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)  
  
### Output: Survival rate, mature plant densities until seed production and seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_3yr\_low\_manipulated <- rot\_3year\_low\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_3yr\_low\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 9)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_3yr\_conv\_original <- rot\_3year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_3yr\_conv\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(original\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 9)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = original\_output, names\_from = variable)  
  
### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_3yr\_low\_original <- rot\_3year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_3yr\_low\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 9)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_3yr\_conv\_all <- N\_3yr\_conv\_lambda\_df %>%  
 left\_join(N\_3yr\_conv\_manipulated\_df) %>%  
 left\_join(N\_3yr\_conv\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

N\_3yr\_low\_all <- N\_3yr\_low\_lambda\_df %>%   
 left\_join(N\_3yr\_low\_manipulated\_df) %>%  
 left\_join(N\_3yr\_low\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

##### with corn under conventional weed management {-}  
N\_4yr\_conv\_lambda <- list() # blank dataframe to save loop output   
  
N\_4yr\_conv\_lambda[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_4yr\_conv\_lambda[[i]] = rot\_4year\_conv\_lambda(vec = N\_4yr\_conv\_lambda[[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\_lambda\_df <- N\_4yr\_conv\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",  
 "cohort\_1", "cohort\_2",  
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything()) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = sqrt(lambda\_cycle),  
 Rotation = "4-year",  
 Corn\_weed\_management = "conventional")   
  
##### with corn under low herbicide weed management {-}   
N\_4yr\_low\_lambda <- list() # blank dataframe to save loop output   
  
N\_4yr\_low\_lambda[[1]] <- starting\_point   
  
for (i in 2:t) {   
 N\_4yr\_low\_lambda[[i]] = rot\_4year\_low\_lambda(vec = N\_4yr\_low\_lambda[[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\_lambda\_df <- N\_4yr\_low\_lambda %>%   
 unlist(recursive = TRUE) %>%  
 data.frame() %>%  
 dplyr::rename(seedbank\_counts = ".") %>%  
 dplyr::mutate(stratum = rep(c("top", "bottom",  
 "cohort\_1", "cohort\_2",  
 "cohort\_3", "cohort\_4",  
 "cohort\_5", "cohort\_6"),t)) %>%  
 filter(stratum %in% c("top", "bottom")) %>%  
 unnest(cols = everything()) %>%  
 mutate(cycle\_no = as.character(rep(1:t, each = 2))) %>%  
 pivot\_wider(names\_from = stratum, values\_from = seedbank\_counts) %>%  
 mutate(total\_seedbank\_counts = top + bottom) %>%  
 mutate(lambda\_cycle = total\_seedbank\_counts/lag(total\_seedbank\_counts),  
 lambda\_annualized = nthroot(lambda\_cycle, 4),  
 Rotation = "4-year",  
 Corn\_weed\_management = "low")

### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
N\_4yr\_conv\_manipulated <- rot\_4year\_conv\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_4yr\_conv\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 12)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)  
  
### Output: Survival rate, mature plant densities until seed production and seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_4yr\_low\_manipulated <- rot\_4year\_low\_manipulated\_outputs(vec = starting\_point,  
 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\_manipulated\_df <- N\_4yr\_low\_manipulated %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 12)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_4yr\_conv\_original <- rot\_4year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_4yr\_conv\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(original\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 12)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "conventional",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = original\_output, names\_from = variable)  
  
### Output: Mature plant densities until seed production (B\_h = sv\_C or sv\_S)  
### 1 iteration only because no randomization at any matrix  
  
N\_4yr\_low\_original <- rot\_4year\_original\_outputs(vec = starting\_point,  
 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\_original\_df <- N\_4yr\_low\_original %>%   
 unlist(recursive = TRUE) %>% # make a long table  
 data.frame() %>%  
 tibble::rownames\_to\_column(., "variable") %>%  
 dplyr::rename(manipulated\_output = ".") %>%  
 dplyr::mutate(cohort = rep(c("1", "2", "3", "4", "5", "6"), 12)) %>%  
 mutate(Crop\_ID = substr(variable, 1, 2),  
 Corn\_weed\_management = "low",  
 variable = substr(variable, 4, 19)) %>%  
 pivot\_wider(values\_from = manipulated\_output, names\_from = variable)

N\_4yr\_conv\_all <- N\_4yr\_conv\_lambda\_df %>%  
 left\_join(N\_4yr\_conv\_manipulated\_df) %>%  
 left\_join(N\_4yr\_conv\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

N\_4yr\_low\_all <- N\_4yr\_low\_lambda\_df %>%   
 left\_join(N\_4yr\_low\_manipulated\_df) %>%  
 left\_join(N\_4yr\_low\_original\_df)

## Joining, by = "Corn\_weed\_management"  
## Joining, by = c("Corn\_weed\_management", "cohort", "Crop\_ID")

mature\_plant\_allowance\_sim\_df %>%  
 mutate(plant\_control\_efficacy = 1 - manipulated\_surv) %>%  
 group\_by(Crop\_ID, Corn\_weed\_management, cohort) %>%  
 summarise(mean\_efficacy = mean(plant\_control\_efficacy)) %>%  
 pivot\_wider(names\_from = cohort, values\_from = mean\_efficacy) %>%  
 mutate(phase\_order = ifelse(str\_detect(Crop\_ID, "C"), 1,  
 ifelse(str\_detect(Crop\_ID, "S"), 2,  
 ifelse(str\_detect(Crop\_ID, "O"), 3, 4)))) %>%  
 mutate(Rot = substr(Crop\_ID,2,2))%>%  
 arrange(Rot, phase\_order, Corn\_weed\_management) %>%  
 mutate\_at(vars(`1`:`6`), funs(round(., 2))) %>%  
 select(Crop\_ID, Corn\_weed\_management, `1`:`6`) %>%  
 flextable() %>%  
 set\_caption("Necessary control efficacy (with respect to seedling survival to maturity) averaged over 100 rotational cycles (the 2-year rotation cycled over two years and ended at the soybean phase, the 3-year rotation cycled over three years and ended at the oat phase, and the 4-year rotation cycled over four years and 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.") %>%  
 set\_header\_labels(values = list(Crop\_ID = "Crop ID",  
 Corn\_weed\_management = "Corn weed management",  
 `1` = "cohort 1",  
 `2` = "cohort 2",  
 `3` = "cohort 2",  
 `4` = "cohort 4",  
 `5` = "cohort 5",  
 `6` = "cohort 6"))

## `summarise()` has grouped output by 'Crop\_ID', 'Corn\_weed\_management'. You can  
## override using the `.groups` argument.

## Warning: `funs()` was deprecated in dplyr 0.8.0.  
## Please use a list of either functions or lambdas:   
##   
## # Simple named list:   
## list(mean = mean, median = median)  
##   
## # Auto named with `tibble::lst()`:   
## tibble::lst(mean, median)  
##   
## # Using lambdas  
## list(~ mean(., trim = .2), ~ median(., na.rm = TRUE))  
## This warning is displayed once every 8 hours.  
## Call `lifecycle::last\_lifecycle\_warnings()` to see where this warning was generated.

Table 1: Necessary control efficacy (with respect to seedling survival to maturity) averaged over 100 rotational cycles (the 2-year rotation cycled over two years and ended at the soybean phase, the 3-year rotation cycled over three years and ended at the oat phase, and the 4-year rotation cycled over four years and 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.

| Crop ID | Corn weed management | cohort 1 | cohort 2 | cohort 2 | cohort 4 | cohort 5 | cohort 6 |
| --- | --- | --- | --- | --- | --- | --- | --- |
| C2 | conventional | 0.99 | 0.99 | 0.99 | 0.96 | 0.96 | 0.99 |
| C2 | low | 1.00 | 1.00 | 1.00 | 0.96 | 0.96 | 0.99 |
| S2 | conventional | 0.99 | 0.99 | 0.99 | 0.74 | 0.99 | 0.99 |
| S2 | low | 1.00 | 1.00 | 1.00 | 0.74 | 0.99 | 0.99 |
| C3 | conventional | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C3 | low | 1.00 | 1.00 | 1.00 | 0.96 | 0.96 | 0.99 |
| S3 | conventional | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| S3 | low | 1.00 | 1.00 | 1.00 | 0.74 | 0.99 | 0.99 |
| O3 | conventional | 0.90 | 0.90 | 0.99 | 0.99 | 0.99 | 0.99 |
| O3 | low | 0.90 | 0.90 | 0.50 | 0.50 | 0.10 | 0.10 |
| C4 | conventional | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| C4 | low | 1.00 | 1.00 | 0.99 | 0.95 | 0.96 | 0.99 |
| S4 | conventional | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| S4 | low | 1.00 | 1.00 | 0.99 | 0.95 | 0.99 | 0.99 |
| O4 | conventional | 0.90 | 0.90 | 0.50 | 0.50 | 0.10 | 0.10 |
| O4 | low | 0.90 | 0.90 | 0.50 | 0.50 | 0.10 | 0.10 |
| A4 | conventional | 0.90 | 0.90 | 0.90 | 0.90 | 0.50 | 0.50 |
| A4 | low | 0.90 | 0.90 | 0.90 | 0.90 | 0.50 | 0.50 |

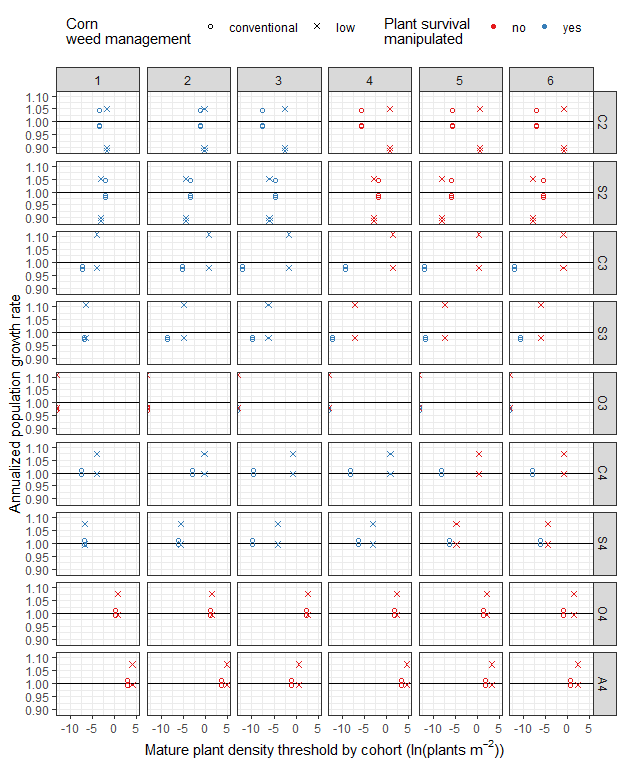


Figure 1: Cohort-based mature plant density thresholds on natural logarithm scale for waterhemp population stabilization averaged over 100 rotational cycles (the 2-year rotation ended at the soybean phase, the 3-year rotation ended at the oat phase, and the 4-year rotation ended at the alfalfa phase). 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 control efficacy on waterhemp 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 for which annualized lambda = 1. However, additional control efficacy was needed in some crop phases outside of the expected groups to reduced the mature plant densities. The black horizontal lines mark lambda = 1. The right-hand-side panel labels indicate the crop identities, which are the combinations of the first letter in crop species names and the rotation to which the crops belonged (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).