

microstegium_elymus_model_summary

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1 Summary

Simulation of *Microstegium vimineum* and *Elymus virginicus* over time. *M. vimineum* is an invasive annual grass and *E. virginicus* is a native perennial grass, with two stages: seedling and adult. Simulations are conducted for each species alone and invading the other after it has had time to establish (100 years). Simulations are also conducted in which both species are introduced to the system at the same time. In the absence of disease, *M. vimineum* is predicted to persist alone, but it is out-competed by *E. virginicus*. In the

presence of disease, the competitive hierarchy reverses: *E. virginicus* can persist alone, but it is outcompeted by *M. vimineum*. *Microstegium vimineum* experiences a net benefit from the presence of disease, likely due to lower intraspecific competition, even though its biomass production and survival are lower. *Elymus virginicus* also experiences losses in biomass and survival in the presence of disease, but intraspecific competition does not decrease. Results were consistent whether species invaded one another or were “co-introduced”.

2 Set-up

```
# clear all existing data
rm(list=ls())

# open libraries
library(data.table)
library(plotly)
library(cowplot)
library(popbio)
library(tidyverse)

# plotting parameters
axisText=10
axisTitle=12
legendText=10
legendTitle=0
colPal = c("#0072B2", "#56B4E9", "#009E73", "#E69F00")

# import data
params <- read_csv("../data/mv_ev_model_parameters_experiment_072420.csv", col_types = cols())
params_dis <- read_csv("../data/mv_ev_model_disease_parameters_experiment_072420.csv", col_types = cols())
```

3 Parameters

3.1 Formatting

- subscripts follow “.”
- A = annual plant
- L = annual litter
- P = perennial adult (at least 1 year old)
- S = perennial seedling (germinated that spring)
- Composite parameters are capitalized

3.2 Settings

```
# simulation time
simtime = 10000

# invasion time
invtime = 6000
```

```

# initial conditions
NO.A = 1 # initial annual population size
NO.S = 1 # initial perennial seedling population size
NO.P = 0 # initial perennial adult population size
LO = 0 # initial annual litter amount
Ni.A = 1 # introduction of annual
Ni.S = 1 # introduction of perennial

```

3.3 “No disease” parameters from experiments

| parameter | symbol | value | units |
|--|----------|---------|--|
| annual germination without litter | g.A | 0.6000 | year ⁻¹ |
| litter suppression of annual germination | beta.A | 1.0300 | g ⁻¹ year ⁻¹ |
| annual seed survival | s.A | 0.1250 | year ⁻¹ |
| annual seedling survival | h.A | 0.9800 | year ⁻¹ |
| annual biomass without competition | v.A | 42.2300 | g year ⁻¹ |
| intraspecific effect of competition on annual | alpha.AA | 0.1900 | year ⁻¹ |
| interspecific seedling effect of competition on annual | alpha.AS | 0.1900 | year ⁻¹ |
| interspecific adult effect of competition on annual | alpha.AP | 0.1300 | year ⁻¹ |
| annual biomass-seed conversion intercept | y.Aint | 34.1500 | seeds g ⁻¹ year ⁻¹ |
| annual biomass-seed conversion slope | y.A | 0.8400 | log-seeds log-g ⁻¹ |
| annual litter-biomass conversion | a | 1.0000 | year ⁻¹ |
| litter decomposition rate | b | 0.6700 | year ⁻¹ |
| perennial germination without litter | g.S | 0.4400 | year ⁻¹ |
| litter suppression of perennial germination | beta.S | 0.0270 | g ⁻¹ year ⁻¹ |
| perennial seed survival | s.S | 0.1100 | year ⁻¹ |
| seedling perennial biomass without competition | v.S | 2.0000 | g year ⁻¹ |
| adult perennial biomass without competition | v.P | 8.4800 | g year ⁻¹ |
| intraspecific seedling effect of competition on perennial seedling | alpha.SS | 0.0068 | year ⁻¹ |
| interspecific effect of competition on perennial seedling | alpha.SA | 0.0140 | year ⁻¹ |
| intraspecific adult effect of competition on perennial seedling | alpha.SP | 0.0470 | year ⁻¹ |
| intraspecific adult effect of competition on perennial adult | alpha.PP | 0.0690 | year ⁻¹ |
| intraspecific seedling effect of competition on perennial adult | alpha.PS | 0.1800 | year ⁻¹ |
| interspecific effect of competition on perennial adult | alpha.PA | 0.0650 | year ⁻¹ |
| perennial seedling biomass-seed conversion intercept | y.Sint | 3.8300 | seeds g ⁻¹ year ⁻¹ |
| perennial seedling biomass-seed conversion slope | y.S | 0.8800 | log-seeds log-g ⁻¹ |
| perennial adult biomass-seed conversion intercept | y.Pint | 6.5800 | seeds g ⁻¹ year ⁻¹ |
| perennial adult biomass-seed conversion slope | y.P | 1.1900 | log-seeds log-g ⁻¹ |
| perennial seedling summer survival | h.S | 0.9800 | year ⁻¹ |
| perennial adult summer survival | h.P | 0.9500 | year ⁻¹ |
| perennial seedling winter survival | w.S | 0.9200 | year ⁻¹ |
| perennial adult winter survival | w.P | 0.9800 | year ⁻¹ |

3.4 “Disease” parameters from experiments

| parameter | symbol | value | units |
|--|--------|--------|------------------------------------|
| annual germination without litter | g.A | 0.6000 | year ⁻¹ |
| litter suppression of annual germination | beta.A | 1.0300 | g ⁻¹ year ⁻¹ |
| annual seed survival | s.A | 0.1250 | year ⁻¹ |

| parameter | symbol | value | units |
|--|----------|---------|--|
| annual seedling survival | h.A | 0.9500 | year ⁻¹ |
| annual biomass without competition | v.A | 26.4700 | g year ⁻¹ |
| intraspecific effect of competition on annual | alpha.AA | 0.0860 | year ⁻¹ |
| interspecific seedling effect of competition on annual | alpha.AS | 0.0780 | year ⁻¹ |
| interspecific adult effect of competition on annual | alpha.AP | 0.1300 | year ⁻¹ |
| annual biomass-seed conversion intercept | y.Aint | 34.1500 | seeds g ⁻¹ year ⁻¹ |
| annual biomass-seed conversion slope | y.A | 0.8400 | log-seeds log-g ⁻¹ |
| annual litter-biomass conversion | a | 1.0000 | year ⁻¹ |
| litter decomposition rate | b | 0.6700 | year ⁻¹ |
| perennial germination without litter | g.S | 0.4400 | year ⁻¹ |
| litter suppression of perennial germination | beta.S | 0.0270 | g ⁻¹ year ⁻¹ |
| perennial seed survival | s.S | 0.1100 | year ⁻¹ |
| seedling perennial biomass without competition | v.S | 1.5700 | g year ⁻¹ |
| adult perennial biomass without competition | v.P | 6.8500 | g year ⁻¹ |
| intraspecific seedling effect of competition on perennial seedling | alpha.SS | 0.0076 | year ⁻¹ |
| interspecific effect of competition on perennial seedling | alpha.SA | 0.0110 | year ⁻¹ |
| intraspecific adult effect of competition on perennial seedling | alpha.SP | 0.0580 | year ⁻¹ |
| intraspecific adult effect of competition on perennial adult | alpha.PP | 0.2600 | year ⁻¹ |
| intraspecific seedling effect of competition on perennial adult | alpha.PS | 0.0430 | year ⁻¹ |
| interspecific effect of competition on perennial adult | alpha.PA | 0.0480 | year ⁻¹ |
| perennial seedling biomass-seed conversion intercept | y.Sint | 3.8300 | seeds g ⁻¹ year ⁻¹ |
| perennial seedling biomass-seed conversion slope | y.S | 0.8800 | log-seeds log-g ⁻¹ |
| perennial adult biomass-seed conversion intercept | y.Pint | 6.5800 | seeds g ⁻¹ year ⁻¹ |
| perennial adult biomass-seed conversion slope | y.P | 1.1900 | log-seeds log-g ⁻¹ |
| perennial seedling summer survival | h.S | 0.8900 | year ⁻¹ |
| perennial adult summer survival | h.P | 0.8800 | year ⁻¹ |
| perennial seedling winter survival | w.S | 0.9000 | year ⁻¹ |
| perennial adult winter survival | w.P | 0.9800 | year ⁻¹ |

4 Model

4.1 Population equations

Assume counts are being conducted in the spring

$$N.A[t+1] = s.A * (1-G.A) * N.A[t] + G.A * h.A * Y.A * N.A[t]$$

annual seeds = seed bank survival + seed production

$$L[t+1] = a * G.A * h.A * V.A * N.A[t] + (1-b) * L[t]$$

annual litter = biomass from previous fall + decomposition

$$N.S[t+1] = s.S * (1-G.S) * N.S[t] + G.S * h.S * Y.S * N.S[t] + h.P * Y.P * N.P[t]$$

perennial seeds = seed bank survival + seedling seed production + adult seed production

$$N.P[t+1] = h.P * w.P * N.P[t] + G.S * h.S * w.S * N.S[t]$$

perennial adults = survival + seedling maturation

4.2 Litter suppression of germination

$$G.A = g.A / (1 + beta.A * L[t])$$

annual seed germination = germination in the absence of litter / reduction due to litter

$$G.S = g.S / (1 + \text{beta}.S * L[t])$$

perennial seed germination = germination in the absence of litter / reduction due to litter

4.3 Density-dependence on growth

$$V.A = v.A / (1 + \text{alpha}.AA * G.A * N.A[t] + \text{alpha}.AP * N.P[t] + \text{alpha}.AS * G.S * N.S[t])$$

annual growth = growth in the absence of competition / (competition from annuals + competition from perennial adults + competition from perennial seedlings)

$$V.S = v.S / (1 + \text{alpha}.SA * G.A * N.A[t] + \text{alpha}.SP * N.P[t] + \text{alpha}.SS * G.S * N.S[t])$$

perennial seedling growth = growth in the absence of competition / (competition from annuals + competition from perennial adults + competition from perennial seedlings)

$$V.P = v.P / (1 + \text{alpha}.PA * G.A * N.A[t] + \text{alpha}.PP * N.P[t] + \text{alpha}.PS * G.S * N.S[t])$$

perennial adult growth = growth in the absence of competition / (competition from annuals + competition from perennial adults + competition from perennial seedlings)

4.4 Seed production based on biomass

$$Y.A = V.A^{y.A} * y.Aint$$

annual seed production = annual biomass with conversion factors (from a log-log regression)

$$Y.S = V.S^{y.S} * y.Sint - 1$$

perennial seedling seed production = perennial seedling biomass with conversion factors (from a log-log regression, 1 added to seed numbers before log-transforming)

$$Y.P = V.P^{y.P} * y.Pint - 1$$

perennial adult seed production = perennial adult biomass with conversion factors (from a log-log regression, 1 added to seed numbers before log-transforming)

5 Function

```
simFun = function(params, NO.A, NO.S, NO.P, LO, Ni.A, Ni.S, simtime, invtime, invader){

  # define parameters
  g.A = filter(params, symbol == "g.A")$value
  beta.A = filter(params, symbol == "beta.A")$value
  s.A = filter(params, symbol == "s.A")$value
  h.A = filter(params, symbol == "h.A")$value
  v.A = filter(params, symbol == "v.A")$value
  alpha.AA = filter(params, symbol == "alpha.AA")$value
  alpha.AS = filter(params, symbol == "alpha.AS")$value
  alpha.AP = filter(params, symbol == "alpha.AP")$value
  y.A = filter(params, symbol == "y.A")$value
  y.Aint = filter(params, symbol == "y.Aint")$value
  a = filter(params, symbol == "a")$value
  b = filter(params, symbol == "b")$value
  g.S = filter(params, symbol == "g.S")$value
  beta.S = filter(params, symbol == "beta.A")$value
  s.S = filter(params, symbol == "s.S")$value
  v.S = filter(params, symbol == "v.S")$value
  v.P = filter(params, symbol == "v.P")$value
```

```

alpha.SA = filter(params, symbol == "alpha.SA")$value
alpha.SS = filter(params, symbol == "alpha.SS")$value
alpha.SP = filter(params, symbol == "alpha.SP")$value
alpha.PA = filter(params, symbol == "alpha.PA")$value
alpha.PS = filter(params, symbol == "alpha.PS")$value
alpha.PP = filter(params, symbol == "alpha.PP")$value
y.S = filter(params, symbol == "y.S")$value
y.Sint = filter(params, symbol == "y.Sint")$value
y.P = filter(params, symbol == "y.P")$value
y.Pint = filter(params, symbol == "y.Pint")$value
h.S = filter(params, symbol == "h.S")$value
h.P = filter(params, symbol == "h.P")$value
w.S = filter(params, symbol == "w.S")$value
w.P = filter(params, symbol == "w.P")$value

# initialize populations
N.A=rep(NA,simtime)
N.S=rep(NA,simtime)
N.P=rep(NA,simtime)
L=rep(NA,simtime)

N.A[1]=NO.A
N.S[1]=NO.S
N.P[1]=NO.P
L[1]=LO

# simulate population dynamics
for(t in 1:(simtime - 1)){

  # introduce invader
  N.A[t] = ifelse(t == invtime & invader == "annual", Ni.A, N.A[t])
  N.S[t] = ifelse(t == invtime & invader == "perennial", Ni.S, N.S[t])

  # reduce germination due to litter
  G.A = g.A / (1 + beta.A * L[t])
  G.S = g.S / (1 + beta.S * L[t])

  # reduce growth due to competition
  V.A = v.A / (1 + alpha.AA * G.A * N.A[t] + alpha.AP * N.P[t] + alpha.AS * G.S * N.S[t])
  V.S = v.S / (1 + alpha.SA * G.A * N.A[t] + alpha.SP * N.P[t] + alpha.SS * G.S * N.S[t])
  V.P = v.P / (1 + alpha.PA * G.A * N.A[t] + alpha.PP * N.P[t] + alpha.PS * G.S * N.S[t])

  # seed production based on biomass
  Y.A = V.A^y.A * y.Aint
  # Y.S = V.S^y.S * y.Sint
  Y.S = V.S^y.S * y.Sint - 1
  Y.S = ifelse(Y.S < 0, 0, Y.S)
  # Y.P = V.P^y.P * y.Pint
  Y.P = V.P^y.P * y.Pint - 1
  Y.P = ifelse(Y.P < 0, 0, Y.P)

  # population size
  N.A[t+1] = s.A * (1-G.A) * N.A[t] + G.A * h.A * Y.A * N.A[t]

```

```

L[t+1] = a * G.A * h.A * V.A * N.A[t] + (1-b) * L[t]
N.S[t+1] = s.S * (1-G.S) * N.S[t] + G.S * h.S * Y.S * N.S[t] + h.P * Y.P * N.P[t]
N.P[t+1] = h.P * w.P * N.P[t] + G.S * h.S * w.S * N.S[t]

# correct to prevent negative numbers
N.A[t+1] = ifelse(N.A[t+1] < 1, 0, N.A[t+1])
L[t+1] = ifelse(L[t+1] < 1, 0, L[t+1])
N.S[t+1] = ifelse(N.S[t+1] < 1, 0, N.S[t+1])
N.P[t+1] = ifelse(N.P[t+1] < 1, 0, N.P[t+1])
}

# save data
dfN = data.frame(time = rep(1:simtime, 4), N = c(N.S, N.P, N.A, L), species = rep(c("Elymus seedling"

# return
return(dfN)
}

```

6 Simulations

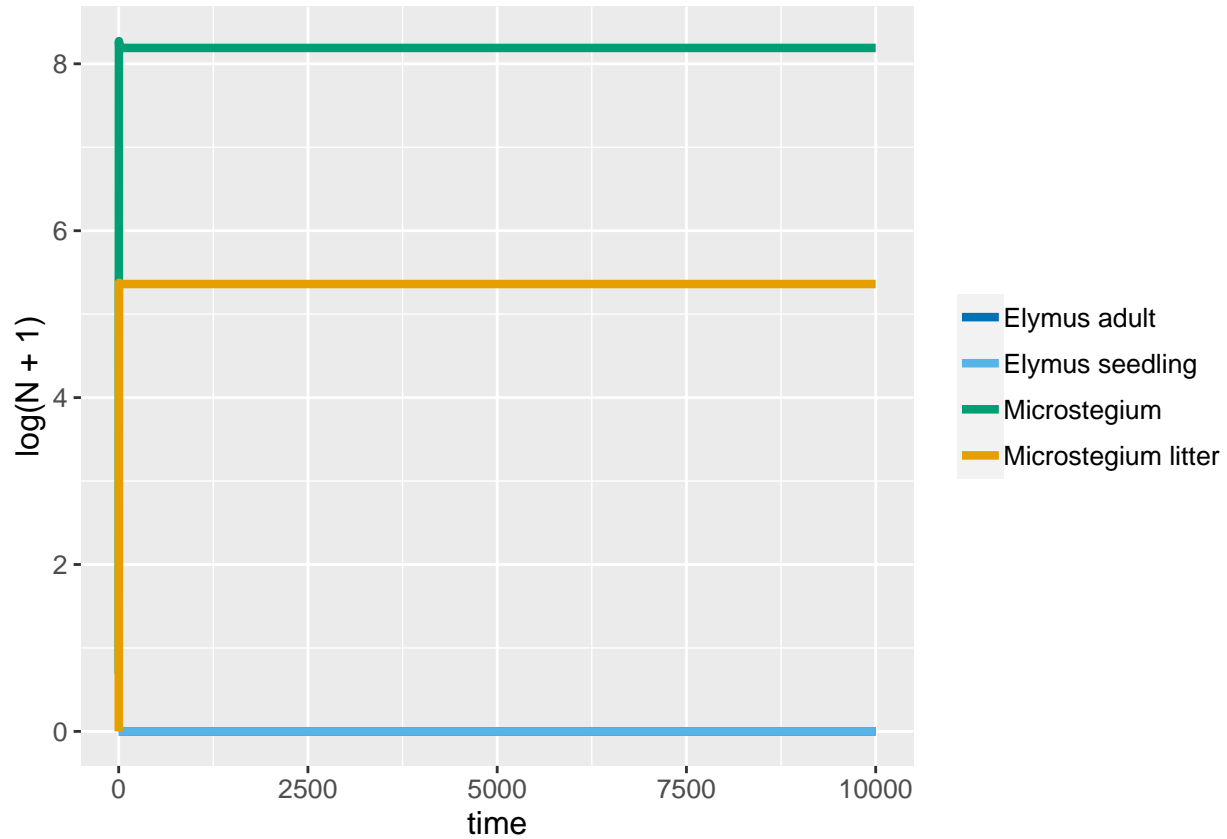
6.1 No disease, Microstegium by itself

```

# run simulation
no_dis_mv_alone_sim <- simFun(params, NO.A, NO.S = 0, NO.P, L0, Ni.A, Ni.S, simtime, invtime, "none")

# figure of time series
no_dis_mv_alone_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
        legend.title = element_text(size = legendTitle)) +
  scale_color_manual(values = colPal)

```

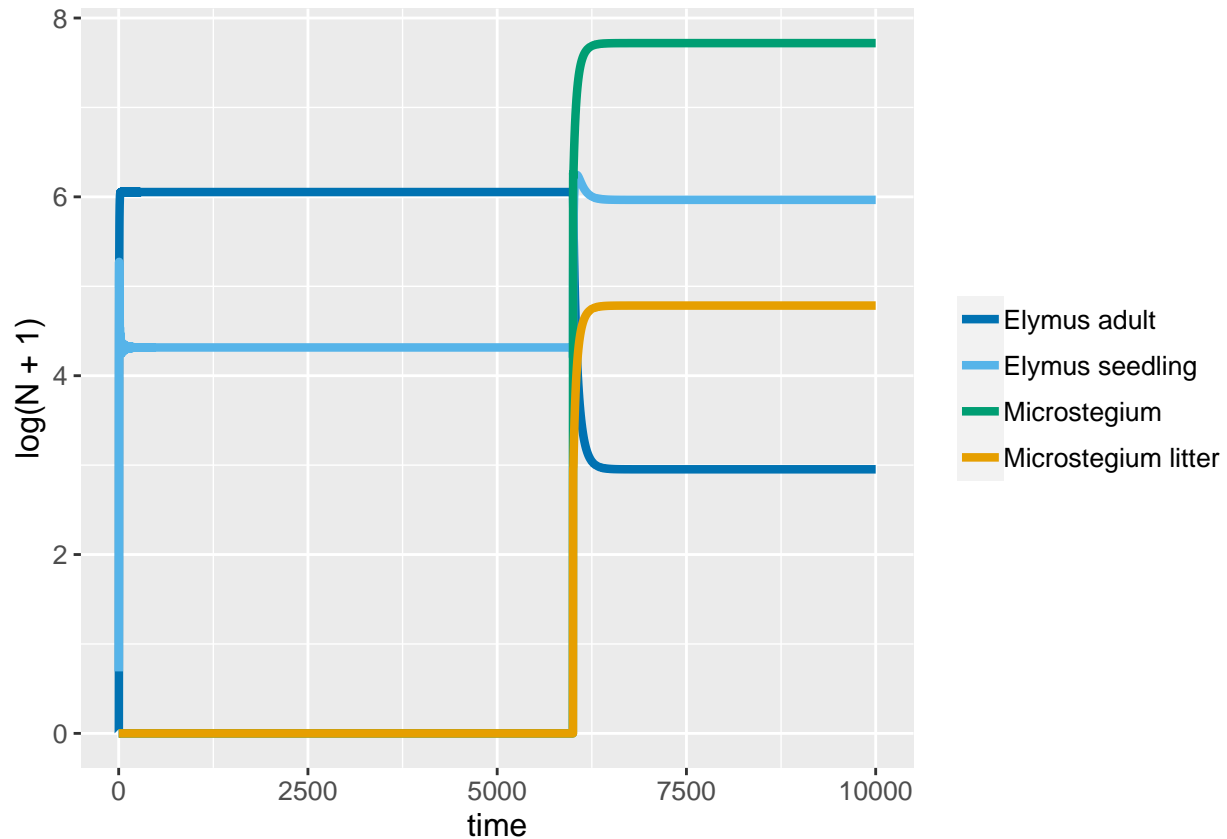


```
# save final density
no_dis_mv_alone_pop <- filter(no_dis_mv_alone_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "Without disease",
         interaction = "alone")
```

6.2 No disease, Microstegium invades Elymus

```
# run simulation
no_dis_mv_invades_sim <- simFun(params, NO.A = 0, NO.S, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "annual")

# figure of time series
no_dis_mv_invades_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
        legend.title = element_text(size = legendTitle)) +
  scale_color_manual(values = colPal)
```

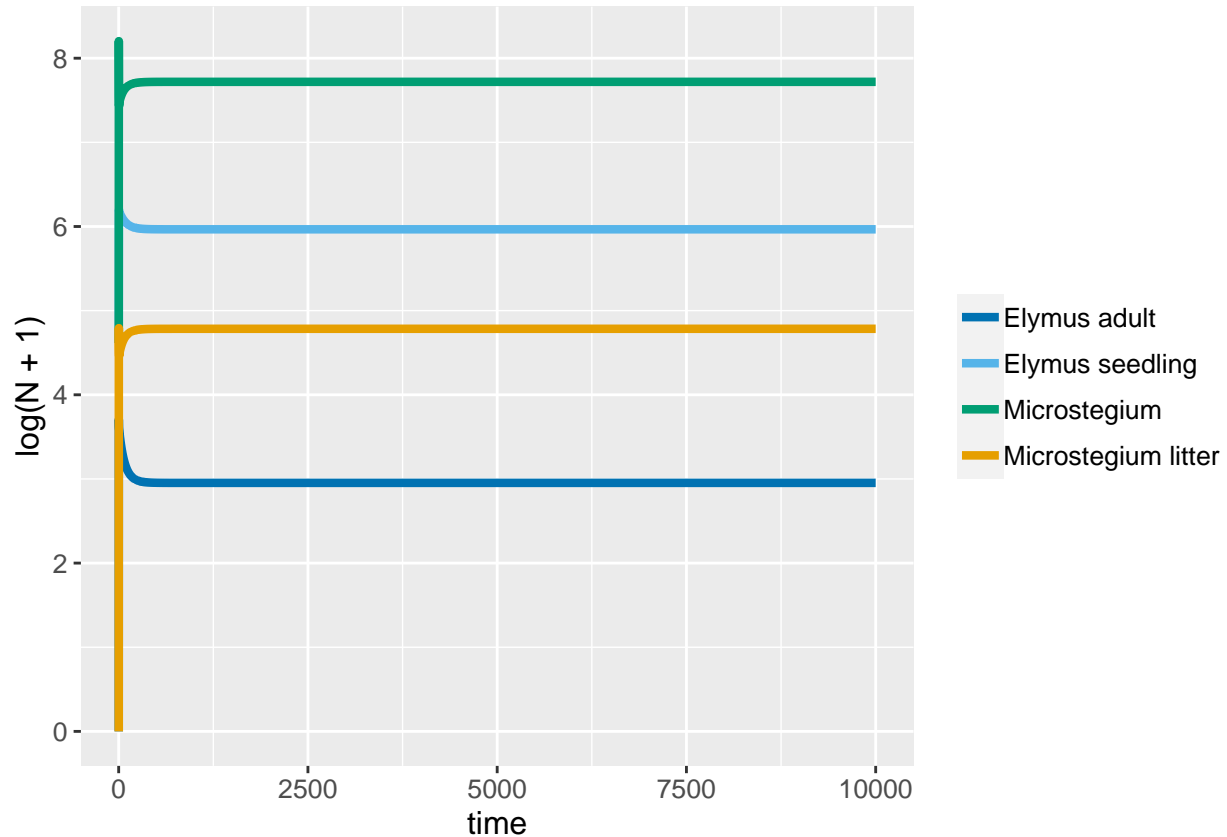



```
# save final density
no_dis_mv_invades_pop <- filter(no_dis_mv_invades_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "Without disease",
         interaction = "invasion")
```

6.3 No disease, co-introduced

```
# run simulation
no_dis_co_intro_sim <- simFun(params, NO.A = 100, NO.S = 100, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "1")

# figure of time series
no_dis_co_intro_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
        legend.title = element_text(size = legendTitle)) +
  scale_color_manual(values = colPal)
```



```
# save final density
no_dis_co_intro_mv_pop <- filter(no_dis_co_intro_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "Without disease",
         interaction = "in competition")

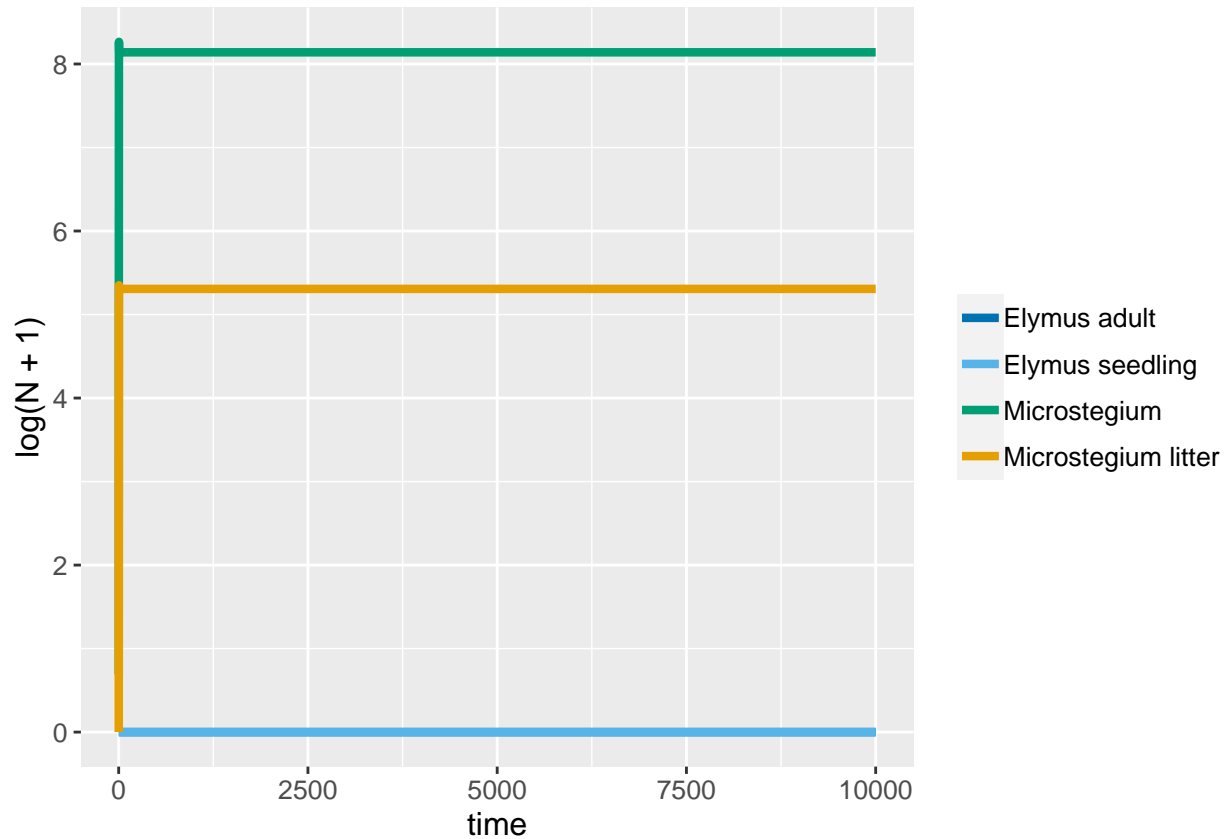
no_dis_co_intro_ev_pop <- filter(no_dis_co_intro_sim, species %in% c("Elymus adult", "Elymus seedling")) %>%
  pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "Without disease",
         interaction = "in competition")
```

6.4 Disease, Microstegium by itself

```
# run simulation
dis_mv_alone_sim <- simFun(params_dis, NO.A, NO.S = 0, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "none")

# figure of time series
dis_mv_alone_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
```

```
legend.title = element_text(size = legendTitle)) +
scale_color_manual(values = colPal)
```

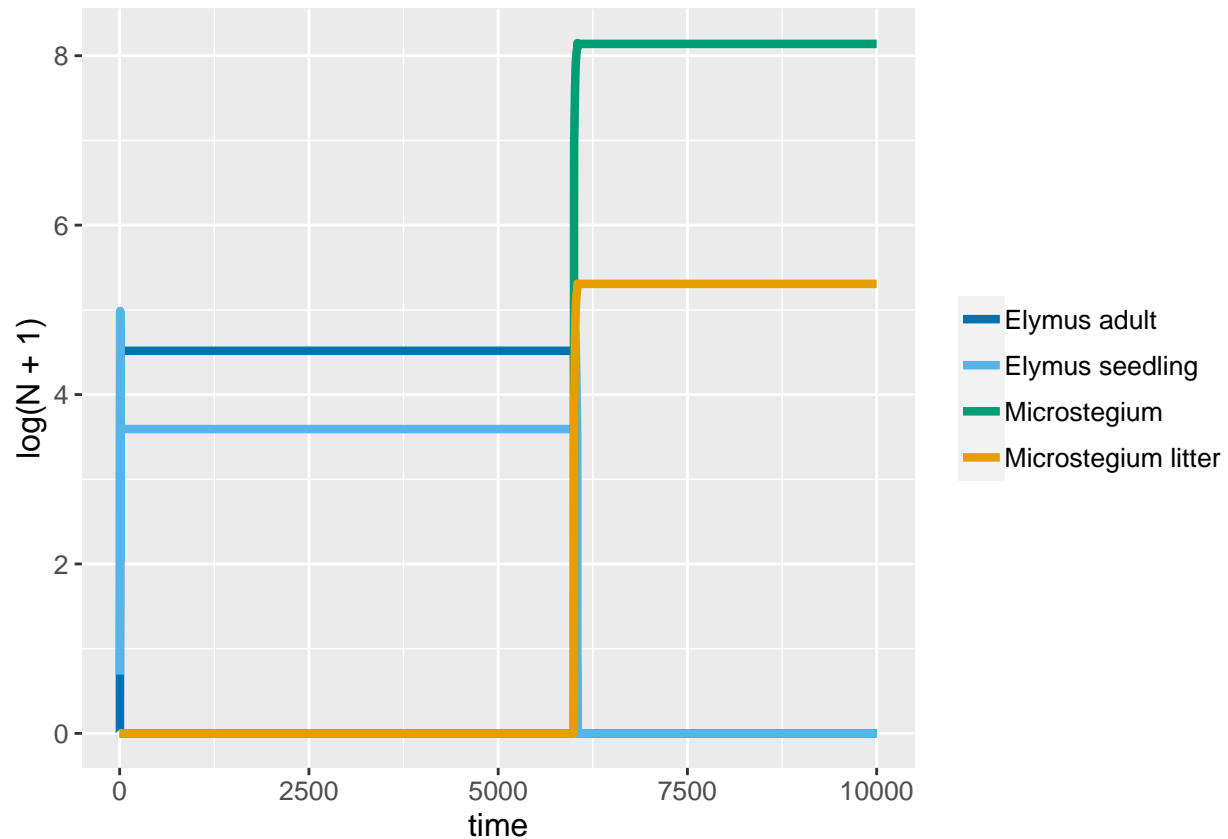


```
# save final density
dis_mv_alone_pop <- filter(dis_mv_alone_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "With disease",
         interaction = "alone")
```

6.5 Disease, Microstegium invades Elymus

```
# run simulation
dis_mv_invades_sim <- simFun(params_dis, NO.A = 0, NO.S, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "annual")

# figure of time series
dis_mv_invades_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
        legend.title = element_text(size = legendTitle)) +
  scale_color_manual(values = colPal)
```

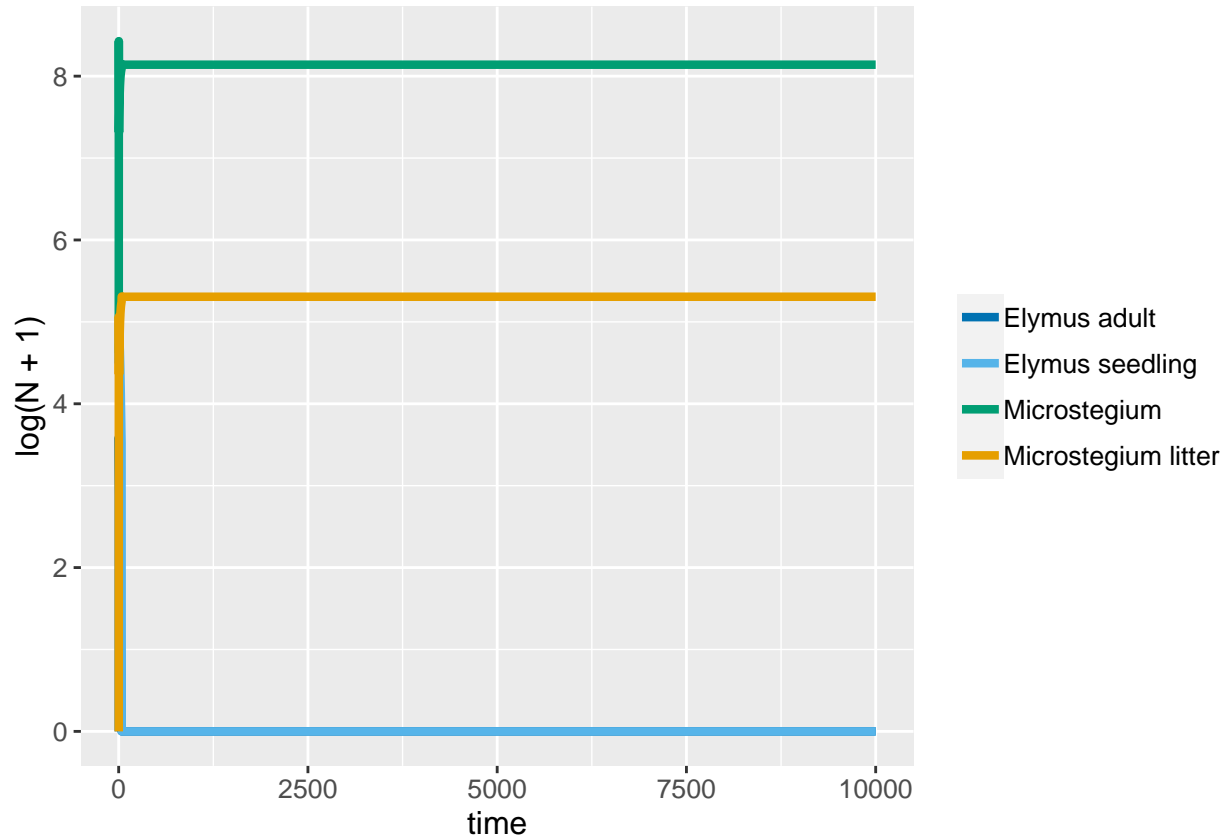


```
# save final density
dis_mv_invades_pop <- filter(dis_mv_invades_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "With disease",
         interaction = "invasion")
```

6.6 Disease, co-introduced

```
# run simulation
dis_co_intro_sim <- simFun(params_dis, NO.A = 100, NO.S = 100, NO.P, LO, Ni.A, Ni.S, simtime, invtime,

# figure of time series
dis_co_intro_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
        legend.title = element_text(size = legendTitle)) +
  scale_color_manual(values = colPal)
```



```
# save final density
dis_co_intro_mv_pop <- filter(dis_co_intro_sim, species == "Microstegium" & time == max(time)) %>%
  mutate(disease = "With disease",
         interaction = "in competition")

dis_co_intro_ev_pop <- filter(dis_co_intro_sim, species %in% c("Elymus adult", "Elymus seedling") & time == max(time)) %>%
  pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "With disease",
         interaction = "in competition")
```

6.7 No disease, Elymus by itself

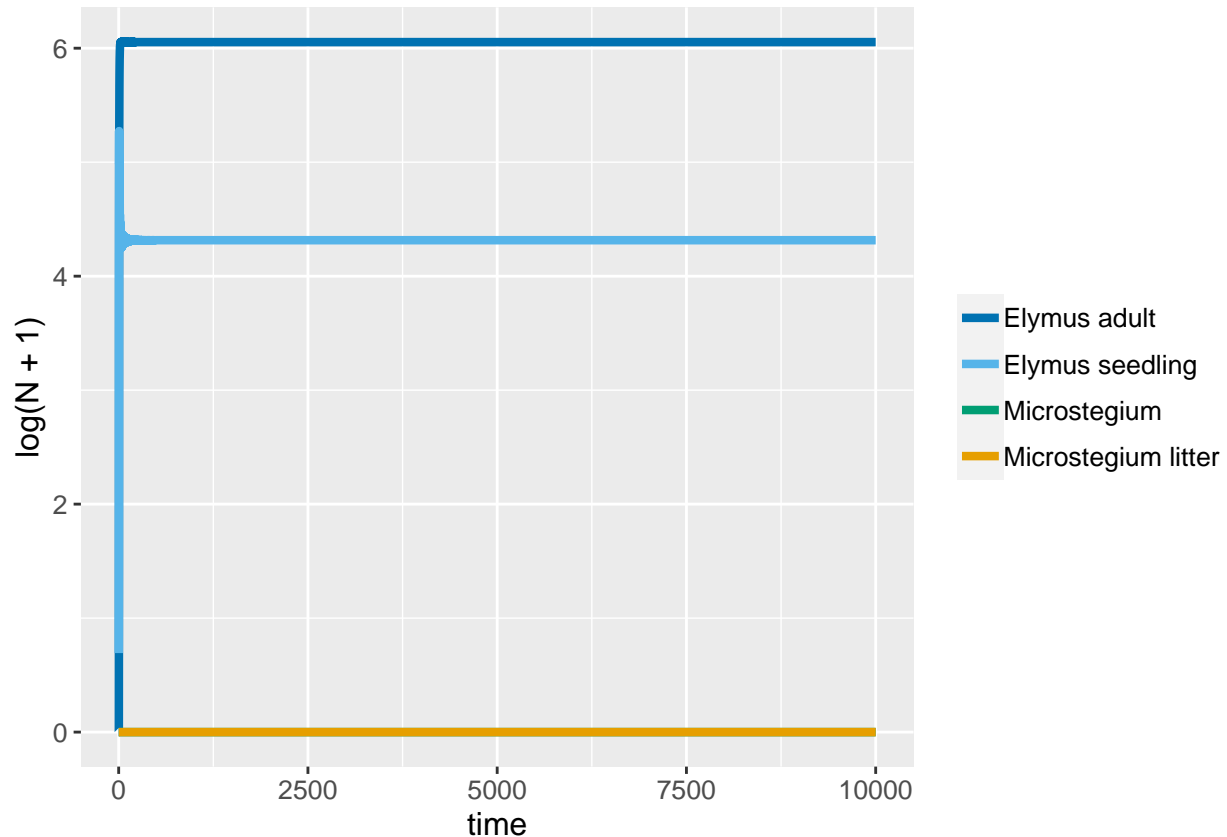
```
# run simulation
no_dis_ev_alone_sim <- simFun(params, NO.A = 0, NO.S, NO.P, L0, Ni.A, Ni.S, simtime, invtime, "none")

# figure of time series
no_dis_ev_alone_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
```

```

    legend.title = element_text(size = legendTitle)) +
    scale_color_manual(values = colPal)

```



```

# save final density
no_dis_ev_alone_pop <- filter(no_dis_ev_alone_sim, species %in% c("Elymus adult", "Elymus seedling")) &
  pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "Without disease",
         interaction = "alone")

```

6.8 No disease, Elymus invades Microstegium

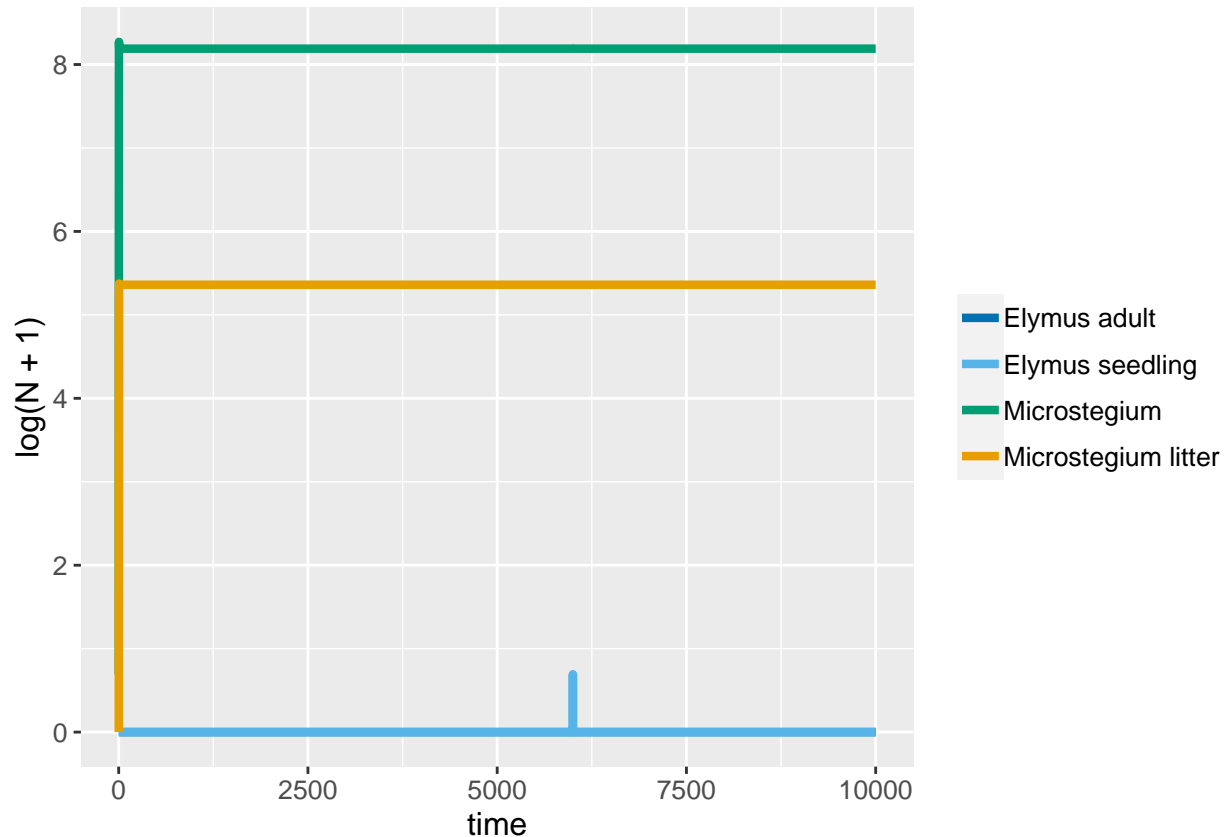
```

# run simulation
no_dis_ev_invades_sim <- simFun(params, NO.A, NO.S = 0, NO.P, L0, Ni.A, Ni.S, simtime, invtime, "perenn")

# figure of time series
no_dis_ev_invades_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),

```

```
legend.title = element_text(size = legendTitle)) +
scale_color_manual(values = colPal)
```



```
# save final density
no_dis_ev_invades_pop <- filter(no_dis_ev_invades_sim, species %in% c("Elymus adult", "Elymus seedling"))
pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "Without disease",
         interaction = "invasion")
```

6.9 Disease, Elymus by itself

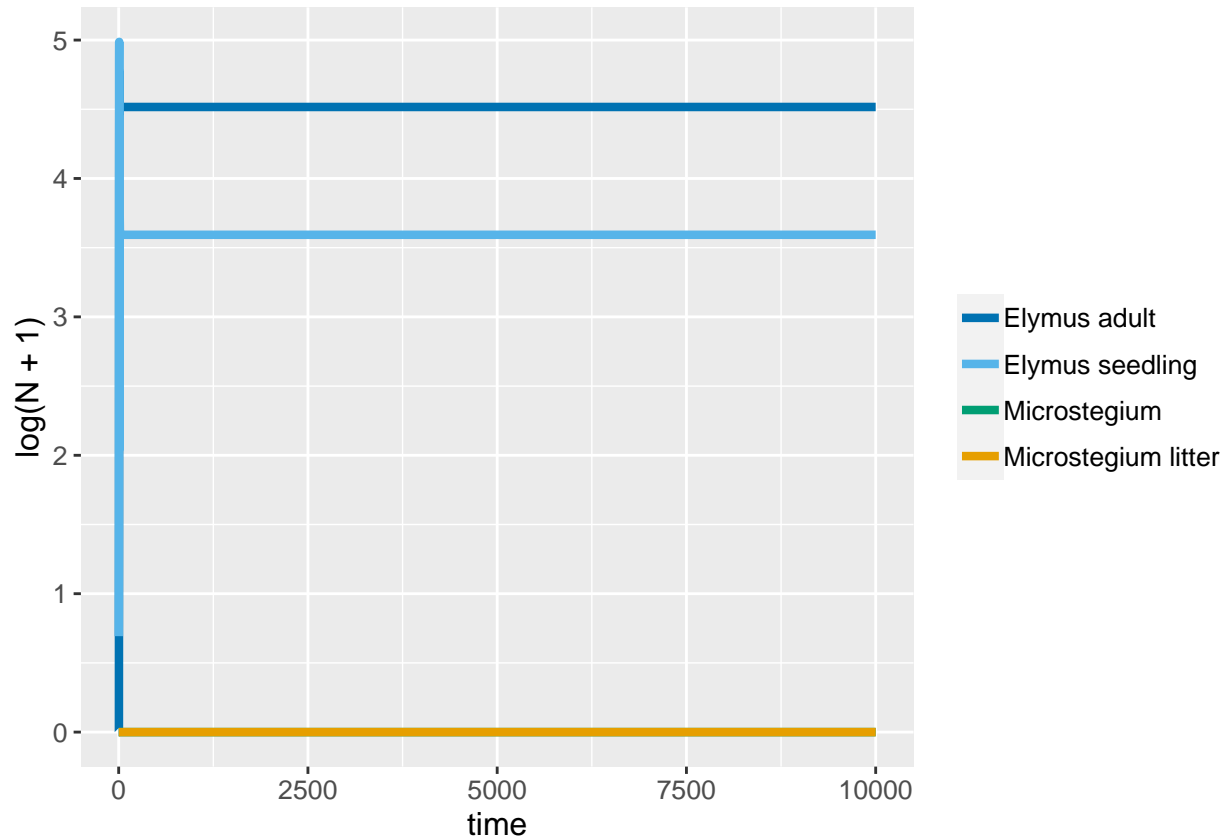
```
# run simulation
dis_ev_alone_sim <- simFun(params_dis, NO.A = 0, NO.S, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "none")

# figure of time series
dis_ev_alone_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),
```

```

legend.title = element_text(size = legendTitle)) +
scale_color_manual(values = colPal)

```



```

# save final density
dis_ev_alone_pop <- filter(dis_ev_alone_sim, species %in% c("Elymus adult", "Elymus seedling") & time == 10000)
pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "With disease",
         interaction = "alone")

```

6.10 Disease, Elymus invades Microstegium

```

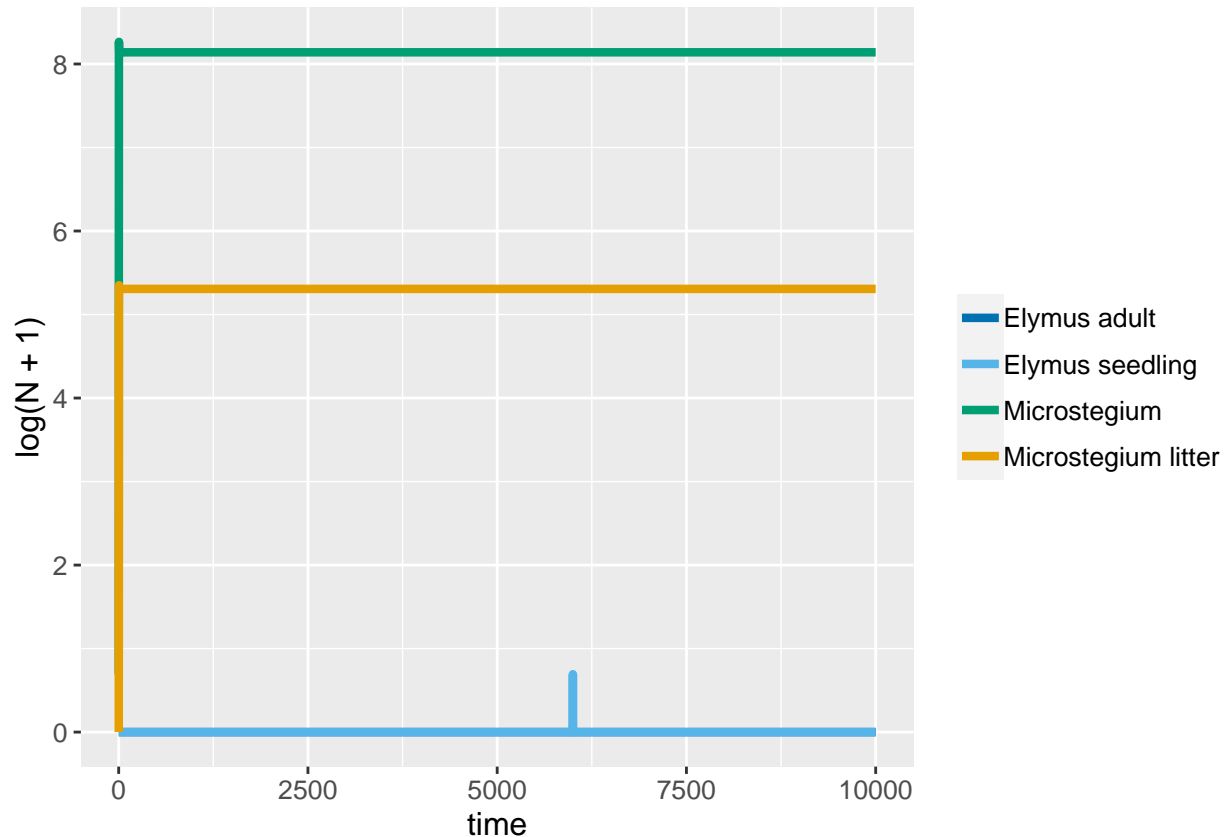
# run simulation
dis_ev_invades_sim <- simFun(params_dis, NO.A, NO.S = 0, NO.P, LO, Ni.A, Ni.S, simtime, invtime, "perennial")

# figure of time series
dis_ev_invades_sim %>%
  ggplot(aes(x = time, y = log(N+1), color = species)) +
  geom_line(size = 1.5) +
  theme(axis.text = element_text(size = axisText),
        axis.title = element_text(size = axisTitle),
        legend.text = element_text(size = legendText),

```



```
legend.title = element_text(size = legendTitle)) +
scale_color_manual(values = colPal)
```



```
# save final density
dis_ev_invades_pop <- filter(dis_ev_invades_sim, species %in% c("Elymus adult", "Elymus seedling") & time == 10000) %>%
  pivot_wider(names_from = species, values_from = N) %>%
  rename("Elymus_adult" = "Elymus adult", "Elymus_seedling" = "Elymus seedling") %>%
  mutate(species = "Elymus",
         N = Elymus_adult + Elymus_seedling,
         disease = "With disease",
         interaction = "invasion")
```

7 Population Figure

```
# combine data
pop_fig_dat <- no_dis_mv_alone_pop %>%
  full_join(no_dis_mv_invades_pop) %>%
  full_join(dis_mv_alone_pop) %>%
  full_join(dis_mv_invades_pop) %>%
  full_join(no_dis_ev_alone_pop) %>%
  full_join(no_dis_ev_invades_pop) %>%
  full_join(dis_ev_alone_pop) %>%
  full_join(dis_ev_invades_pop) %>%
  mutate(species = recode(species, "Microstegium" = "M. vimineum", "Elymus" = "E. virginicus")) %>%
```

```

    fct_relevel("M. vimineum"),
    log_N = log(N + 1),
    disease = fct_relevel(disease, "Without disease"))

## Joining, by = c("time", "N", "species", "disease", "interaction")
## Joining, by = c("time", "N", "species", "disease", "interaction")
## Joining, by = c("time", "N", "species", "disease", "interaction")
## Joining, by = c("time", "N", "species", "disease", "interaction")

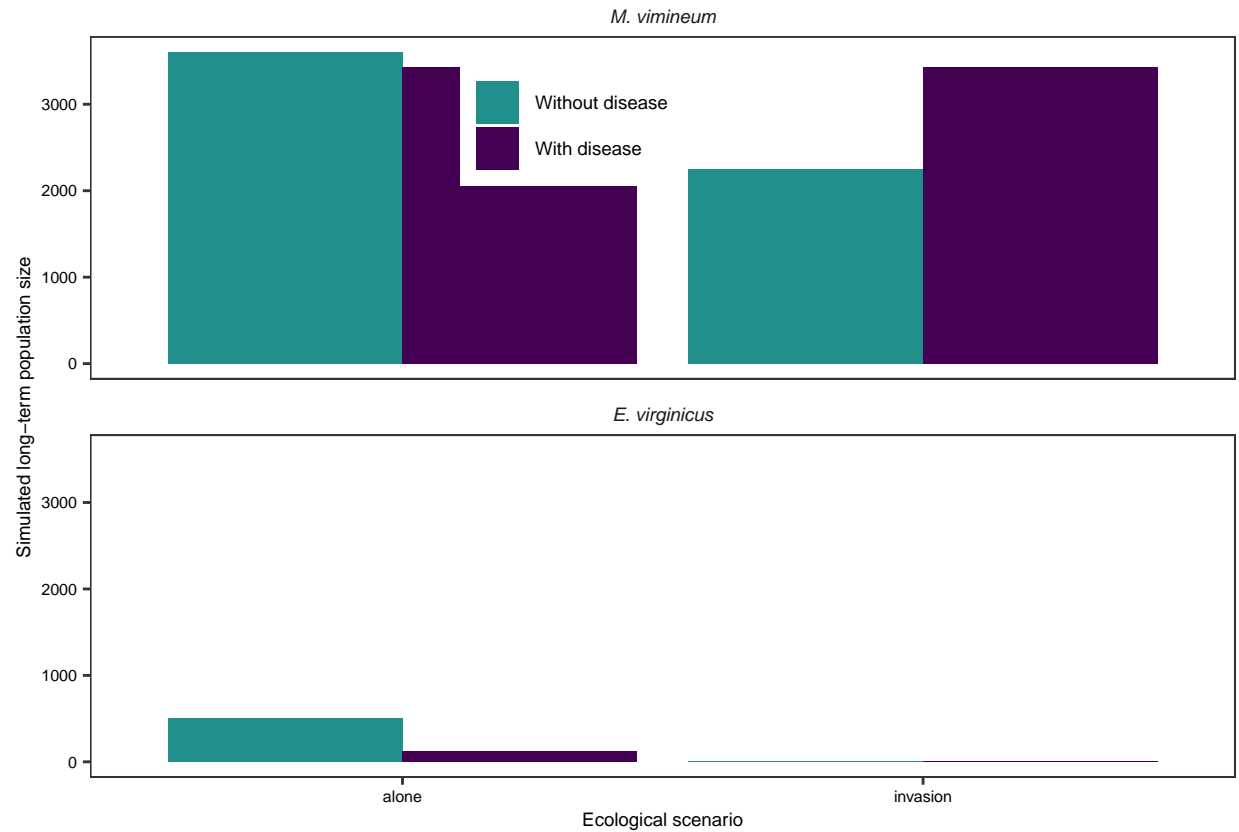
## Joining, by = c("time", "N", "species", "disease", "interaction", "Elymus_seedling", "Elymus_adult")
## Joining, by = c("time", "N", "species", "disease", "interaction", "Elymus_seedling", "Elymus_adult")
## Joining, by = c("time", "N", "species", "disease", "interaction", "Elymus_seedling", "Elymus_adult")

# template theme
temp_theme <- theme_bw() +
  theme(axis.text = element_text(size = 6, color="black"),
        axis.title = element_text(size = 7),
        panel.background = element_blank(),
        panel.grid.major = element_blank(),
        panel.grid.minor = element_blank(),
        legend.text = element_text(size = 7),
        legend.title = element_blank(),
        legend.box.margin = margin(-10, -10, -10, -10),
        legend.position = c(0.42, 0.89),
        strip.background = element_blank(),
        strip.text = element_text(size = 7, face = "italic"),
        strip.placement = "outside",
        plot.title = element_text(size = 7, hjust = 0.5))

# colors
col_pal = c("#21908CFF", "#440154FF")

# figure
pop_fig <- ggplot(pop_fig_dat, aes(x = interaction, y = N)) +
  geom_bar(stat = "identity", position = "dodge", aes(fill = disease)) +
  scale_fill_manual(values = col_pal) +
  facet_wrap(~species, nrow = 2) +
  xlab("Ecological scenario") +
  ylab("Simulated long-term population size") +
  temp_theme
pop_fig

```



```
# save figure
pdf("../output/simulated_long_term_pop_figure.pdf", width = 2, height = 4)
pop_fig
dev.off()
```

```
## pdf
## 2
```