Using a Chemical Arsenal for a Competitive Advantage: Garlic Mustard Invasion

Project Module Associated with
Introduction to Computational Science:
***Modeling and Simulation, 2nd Edition* by**

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Prerequisites for Project 1: *Module 2.2, "Unconstrained Growth and Decay," and for Part b, section "Sensitivity Analysis for Age-Structured Example" of Module 13.3, "Time after Time: Age- and Stage-Structured Models"*
Prerequisite for Project 2: *Module 8.3, "Empirical Models"*
Prerequisites for Project 3: *Module 8.3, "Empirical Models," and Module 2.2, "Unconstrained Growth and Decay;" and for Part b, section "Sensitivity Analysis for Age-Structured Example" of Module 13.3, "Time after Time: Age- and Stage-Structured Models"*
Prerequisite for Project 4: *One of Module 10.3 on "Spreading of Fire," Module 10.4 on "Movement of Ants–Taking the Right Steps," or Module 10.5 on "Biofilms: United They Stand, Divided They Colonize"*

Introduction

Invasive species of plants may outcompete native plants, often reducing plant diversity significantly. In the United States, an herbaceous plant, *Alliaria petiolata* (garlic mustard), was introduced from Europe to Long Island, NY about 150 years ago. Used for food and medicinal purposes, this plant has spread throughout many forest and forest fringe areas in the Eastern U.S. and Canada, as well as to some western states of the U.S. and British Columbia. It has replaced numerous native species by reducing available light, nutrients, and water (CUCE 2016). The USDA classifies it as a class A noxious weed or prohibited invasive species (USDA NRCS 2007).

Fairly typical of invasive plant species, garlic mustard has a very complex life cycle, making its control or eradication very challenging (Pardini, et al 2009). Seeds, produced by the hundreds or thousands per plant a year or two prior, germinate in the spring (March- May). Seedlings mature into **rosettes** (leaves arranged circularly, often at the soil surface) by mid-summer, which overwinter. During early spring, the rosettes grow upward (bolt) to form flowering plants, which produce seed. These seed require **stratification** (exposure to sufficiently cold temperatures during the winter). Some of the seed may germinate the following spring, or may remain **dormant** (non-germinated) for several years. Interestingly, if we clip the flowers prior to seed production, the plant may re-bloom, although the subsequent flowers produce fewer seed (Shyu, et al 2013).

Garlic mustard displays what ecologists call an **overcompensatory** population growth curve. Such a growth curve is generated by an inverse relationship between adult populations and juvenile survival success (Zipkin et al. 2009). In other words, as the density of adult plants decreases, the number of juvenile plants that survive increases, and vice versa. Moreover, as the density of the adults and juveniles decrease, the probability that rosettes survive the summer increases, and vice versa (Pardini 2009). Therefore, control efforts centered on removing the adult plants may only serve to increase the survival of the next generation of adult plants. Perversely, thinning rosettes in the summer may also increase the chance that the remaining juveniles will survive the winter (Pardini 2009).

Invasive species, such as garlic mustard, may compete directly with other organisms by decreasing or denying access to one or more resources. This type of competition, termed **interference competition**, may employ physical contests or subtler means, such as **allelopathy**. Allelopathy involves the production and release of toxic chemicals that inhibit the growth of competitors. Many of the best examples of allelopathic chemicals are those produced by plants, like the garlic mustard. The chemicals may reside in any part of a plant (e.g., leaves, flowers, stems, roots) and may persist in the soil for long periods of time. The chemicals may act to inhibit any of a number of biological processes necessary for the life of competitors. For example, the chemical might inhibit seed germination or root growth (Ferguson et al 2013; Rivenshield, 2002). Evidence has shown that garlic mustard may, along with other competitive tools, produce chemicals that inhibit **mycorrhizae** in forest communities. Mycorrhizae are soil fungi, which colonize the root systems of various plant species. The fungi acquire organic food that is produced by the plant, and the fungi transfer various nutrients and water to the plant. Without the fungi, the associated plants are unable to grow as successfully (Burke 2008).

Exercises

1. In an experiment by Baskin and Baskin (1992), 554 out of 900 garlic mustard seeds germinated the first year; and over the next 3 years, an additional 72 seeds germinated. If we assume that after this period, seeds are not viable, find the viability, v, of garlic mustard seeds. (Other scientists have found other values of viability.)

2. Assuming a viability of 0.8228 and using the experimental data in Table 1, estimate g_1, the probability of seeds that are viable germinating the following year

Seeds Planted	Seeds Germinated
500	86
250	76
250	144
250	121

Table 1 Results of germination experiments after the first winter (Anderson et al. 1996)

3. Using the following experimental data, estimate g_2, the probability of germination for seeds in at least their second year and in the seed bank. Assume a viability of

0.8228. Of 500 seeds planted, 86 germinated in the first year, and 12 germinated their second spring (Anderson et al. 1996).

4. Using data and empirical modeling, Pardini et al. (2011) derived the following models for f, s_2, and s_3, where A, R, and R_{Aug} are the adult, rosette, and August rosette densities, respectively:

$$f = e^{7.48933 - 0.03893A}$$

$$s_2 = \frac{1}{1 + e^{-0.11635 + 0.01612A + 0.00144R + 0.00092AR}}$$

$$s_3 = \frac{1}{1 + e^{-1.32702 + 0.50269\ln(R_{Aug}+1)}}$$

Plot each of the functions, and describe how f, s_2, and s_3 vary with respect to their independent variables.

Projects

1. Suppose the fertility, f, of garlic mustard is the average number of seeds per plant; and the viability rate of the seeds is v. With a probability of g_1, seeds that are viable germinate the following year; otherwise, these viable seeds enter the seed bank. Seeds in the seed bank (i.e., seeds that are at least in their second year) germinate with a probability of g_2; otherwise, these seeds remain in the seed bank. We assume that viable seeds remain viable indefinitely. The probability that a germinated seed will survive to the rosette stage is s_1; otherwise, they die. The probability that rosettes survive from early May to August, s_2, can be a function of adult and rosette densities; while the probability that rosettes survive from August to early May, s_3, when they mature into adults is only a function of August rosette density. All adults die after producing seed (Pardini et al. 2009). Based on data, Pardini et al. estimated that $v = 0.8228$ (varying in range 0.7 - 1.0), $g_1 = 0.5503$ (varying in range 0.1 – 0.9), $g_2 = 0.3171$ (varying in range 0.01 – 0.6), and $s_1 = 0.131$. For simplification, we assume that s_1 is constant although the probability of germinated seed survival to the rosette stage is likely to be greater when the density of adults is smaller.

a. Using the models for f, s_2, and s_3 from Exercise 4, develop a system dynamics model of garlic mustard with systems for seeds in seed banks, rosettes, and adults. For the calculation of s_3, be sure to use the number of rosettes that survive the summer.

b. Determine the percentage efforts of killing rosettes, adults, or both to eliminate the garlic mustard. Assume that management efforts occur in May. Thus, to reduce rosettes in the model, multiply s_2 by a fraction between 0 and 1. Similarly, to reduce adults, multiply s_3 by a fraction between 0 and 1. Discuss the situation and recommendations for management.

c. Using sensitivity analysis, determine the variable v, g_1, g_2, or s_1 to which the model is most sensitive.

2. **a.** Determine an empirical model for the data in Table 2a; that is determine a function that captures the trend of the fertility, f (average number of seeds per plant), of garlic mustard based on adult density (number of adults per 1-m^2 plot) in May.

c. Using the data in Table 2b, determine an empirical model of the probability of summer survival, s_2, of garlic mustard rosettes versus the adult density (number of adults per 1-m^2 plot) in May, when the mean rosette density is 78.04348.

b. Using the data in Table 2c, determine an empirical model of the probability of winter survival, s_3, of garlic mustard rosettes versus the rosette density (number of adults per 1-m^2 plot) in August.

a

May Adult Density	f
2	950
2	1400
2	1450
2	1550
2	1750
2	1800
2	2100
2	2150
2	2300
2	2700
2	3300
3	1350
3	1450
4	1250
4	1400
8	2100
9	900
16	800
16	900
17	850
18	750
19	1050
20	1000
32	400
33	400
38	500
49	500
50	400

b

May Adult Density	s_2
1	0.58
2	0.63
2	0.67
2	0.76
2	0.83
2	1.00
3	0.28
3	0.36
4	0.21
4	0.37
8	0.42
9	0.24
16	0.14
16	0.24
17	0.19
18	0.17
19	0.06
20	0.06
32	0.04
33	0.09
38	0.04
49	0.07
50	0.08

c

August Rosette Density	s_3
5	1.00
6	0.48
10	0.60
15	0.33
20	0.48
30	0.48
40	0.38
45	0.35
50	0.32
55	0.34
140	0.24
145	0.23
160	0.24
260	0.19
290	0.18

Table 2 **a.** Fertility, f (average number of seeds per plant), of garlic mustard based on the adult density (number of adults per 1-m^2 plot) in May. **b.** The probability of summer survival, s_2, of garlic mustard rosettes versus the adult density (number of adults per 1-m^2 plot) in May, when the mean rosette density is 78.04348. **c.** The probability of winter survival, s_3, of garlic mustard rosettes based on the rosette density (number of adults per 1-m^2 plot) in August. (Data approximated from graphs in Appendix A of Pardini et al. 2011)

3. Refer to the information in the "Introduction" and Project 1.

a. Develop a system dynamics model of garlic mustard with systems for seeds in seed banks, rosettes, and adults. Use the models for f, s_2, and s_3 from Project 2 instead of the functions in Project 1, and start with one seed. Note that this model for s_2 is a simplification as the function only depends on adult density when mean rosette density is 78.04348.

b. For this model, repeat Project 1, Part b.
c. For this model, repeat Project 1, Part c.

4. Refer to the information in the information in the "Introduction" and Project 1.
a. Develop a cellular automaton model of garlic mustard. Instead of using the models for f, s_2, and s_3 from Project 1, base density-dependent decisions for the next state of a cell on the contents of its Moore neighborhood.
b. Determine the percentage efforts of killing rosettes, adults, or both to eliminate the garlic mustard. Discuss the situation and recommendations for management.

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