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Theoretical modeling of the tradeoffs limiting root architecture plasticity

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Introduction

Root plasticity plays an important role in plant resource acquisition, and has important implications for adaptation and competition in heterogeneous environments (4,5). Substantial genotypic variation for root architecture plasticity exists, which suggests that tradeoffs may limit the usefulness of plasticity in nature (1,2). A shallower root system is advantageous in low-phosphorus soils because it enhances root exploration and topsoil foraging, which results in increased phosphorus uptake efficiency and increased plant productivity (5). At the same time, optimal rooting depth for multiple resource acquisition ultimately depends on the relative scarcity and localization of one resource compared with the other (3). We have developed a theoretical model to explore the possible tradeoffs that limit root architecture plasticity in response to phosphorus availability and to study the distribution of plastic (P) and nonplastic (N) plants in a population over time. Specifically, plastic plants in our model can condition upon the phosphorus availability by altering the shallowness of their root system. We identify two potential mechanisms, which we address individually and in combination, that allow for the existence of nonplastic phenotypes in nature: 1) a fluctuating drought environment and 2) spatial competition between neighboring plants.

Model Description

- Population of plastic (P) and nonplastic (N) plants of mass = 1
- X and Y are two random variables, denoting phosphorus and water status, respectively
- The choice variable of each plant is the depth at which to grow its roots, denoted as *d*
- The payoff to a plant is the number of offspring produced and is denoted $\pi(d_t, x_t, y_t)$
- Time is infinite, discrete and indexed by $t = 0, 1, 2$
- Steady state equilibrium (q^*) occurs when the expected distribution of plastic plants in the next period, q_{t+1} is exactly equal to the distribution in the current period, q_t.
- Law of motion is given by: $$q_{t+1} = \frac{q_t \pi^P(d(x_t), x_t, q_t)}{q_t \pi^P(d(x_t), x_t, q_t) + (1-q_t)\pi^N(d^N, x_t, q_t)}$$

Model Part 1: Fluctuating drought environment

Nonplastic plant payoff: $\pi(d^N, x_t, y_t)$

Plastic plant payoff: $\pi(d(x_t), x_t, y_t)$

$$q^*(EP_1 - EN_1) = (EP_1 - EN_1)$$

Model Part 2: Spatial competition

Nonplastic plant payoff: $q_t \pi(d^N, x_t)$

Plastic plant payoff: $(1 - q_t)\pi(d(x_t), x_t)$

$$q^* = \frac{EP_2}{EP_2 + EN_2}$$

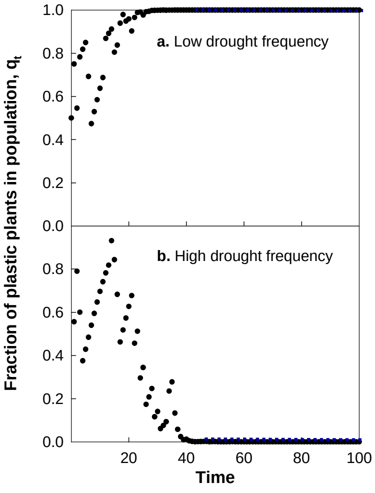
Model Part 3: Combining fluctuating drought & spatial competition

Nonplastic plant payoff: $q_t\ \pi(d^N, x_t, y_t)$

Plastic plant payoff: $(1 - q_t)\ \pi(d(x_t), x_t, y_t)$

$$q^* = \frac{EP_3}{EP_3 + EN_3}$$

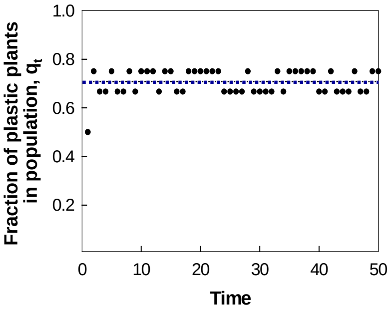
Part 1: Fluctuating drought environment



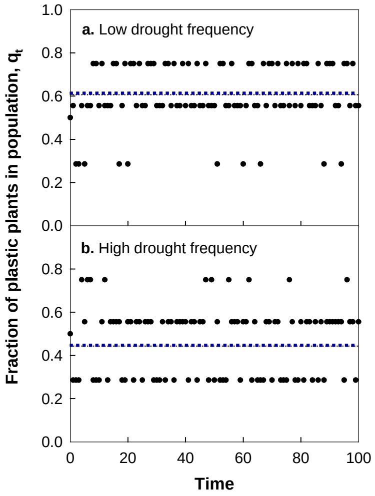
- **Fluctuating drought environment allows for the existence of nonplastic plants, but it does not allow for the coexistence of both genotypes in a single population**
- **Plastic plants dominate the population at low drought frequency**
- **Nonplastic plants dominate the population at high drought frequency**
- **Increased drought susceptibility may be a tradeoff to developing a shallow root system in response to low phosphorus availability**

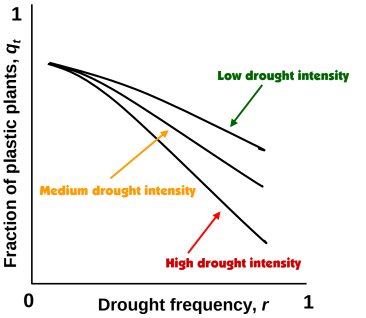
Part 2: Spatial competition

- **Plastic and nonplastic plants coexist at steady state equilibrium**
- **Plastic plants will always be a higher fraction of the population at equilibrium**
- **Spatial competition is an additional tradeoff to root plasticity**



Part 3: Interaction of drought & spatial competition





- **Plastic and nonplastic plants coexist at steady state equilibrium**
- **Steady state equilibrium is dependent upon the drought frequency**
- **Increasing drought intensity results in an increase in the sensitivity of plastic plants to drought frequency**
- **Interaction of coexistence mechanisms affects both the steady state equilibrium and the variation around the population mean**

Conclusions

Our model supports the hypotheses that a fluctuating drought environment and spatial competition are both tradeoffs limiting root architecture plasticity to phosphorus availability. The model also shows the importance of the interaction between these factors in determining population composition and dynamics over time. As shown in Part 1, the success of plastic phenotypes is limited when there is a high frequency of drought. A fluctuating drought environment does not, however, allow for the coexistence of both plastic and nonplastic plants in a given population, as only one type or the other will persist, depending on the drought frequency. Spatial competition, on the other hand, does allow for the coexistence of both plastic and nonplastic phenotypes as a stable fraction of the population as shown in Part 2. When both fluctuating drought environments and competition are considered together in Part 3, coexistence of nonplastic and plastic phenotypes is maintained, but in this case, the steady state proportion of plastic and nonplastic phenotypes is dependent upon the drought frequency.

Acknowledgments

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References Cited

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