Analysis of conditions necessary for mycorrhizal mutualism through a mechanistic model of nutrient exchange

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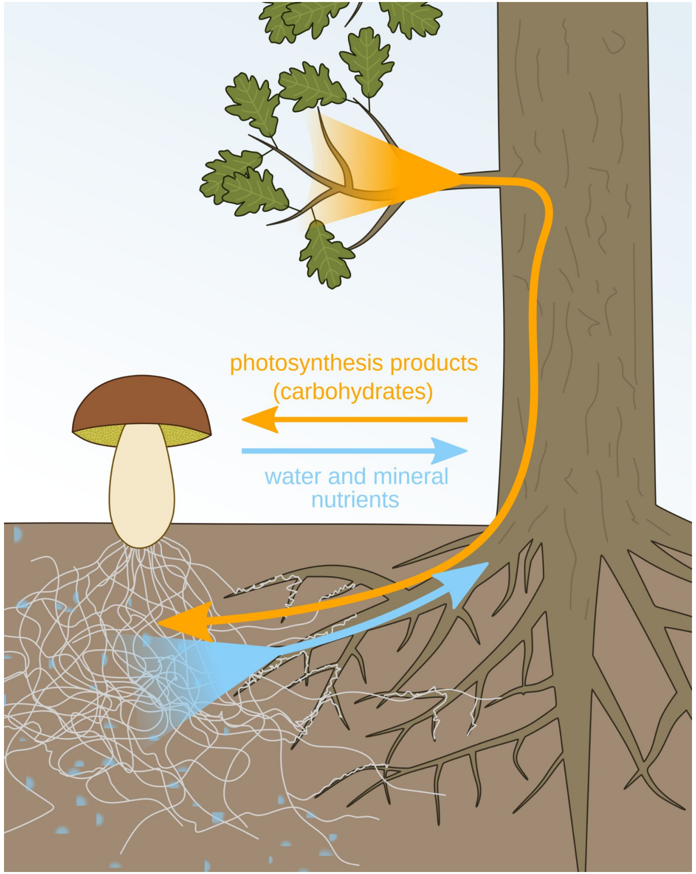
Types of relationships in ecological theory

- Organisms can interact in various ways
- Mutualism (+/+): both organisms benefit from the relationship
- Commensalism (0/+): one organism benefits, the other is unaffected
- Parasitism (+/-): one organism benefits at the expense of the other, by living on or in its body
- Predation (+/-) one organism benefits at the expense of the other, by killing and eating it

Mycorrhizal relationships

- Trees and fungi exchange nutrients through mycorrhiza (a belowground relationship)
- Fungus needs carbon (C) from tree
- Tree needs nitrogen (N) from fungus
- Active debate: is this relationship mutualistic?



Wang et al., *Molecular Plant* 2017
Stuart & Plett, *Frontiers in Plant Science* 2020

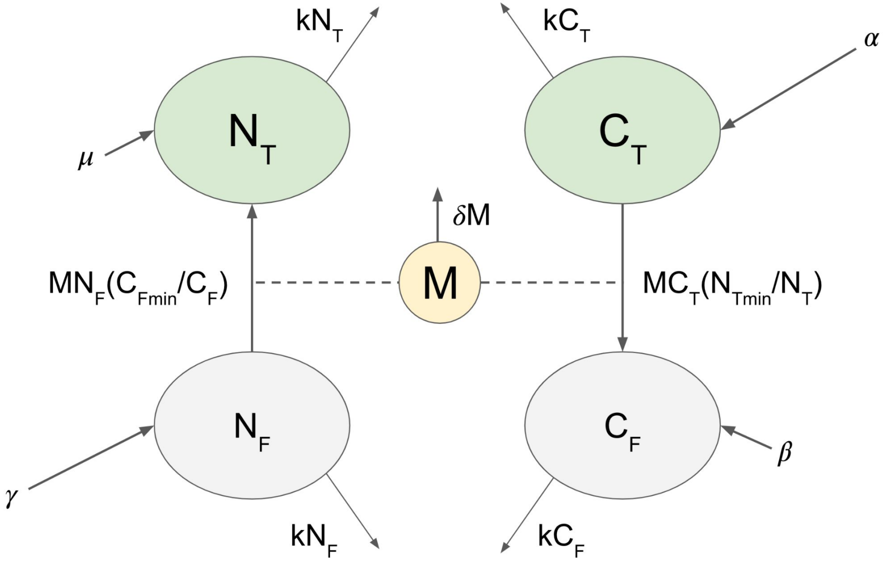
Image: Wikimedia commons

Research question

- **What are the environmental conditions required to produce a stable mutualistic exchange of nutrients in the mycorrhiza?**
- Understanding this relationship would help keep forests healthy

Image: Eco Farming Daily

Mechanistic model of mycorrhizal nutrient exchange



$$\frac{dC_T(t)}{dt} = \alpha - kC_T(t) - M(t)C_T(t)\frac{N_{Tmin}}{N_T(t)} \quad \text{(Eq. 1)}$$

$$\frac{dN_F(t)}{dt} = \gamma - kN_F(t) - M(t)N_F(t)\frac{C_{Fmin}}{C_F(t)} \quad \text{(Eq. 2)}$$

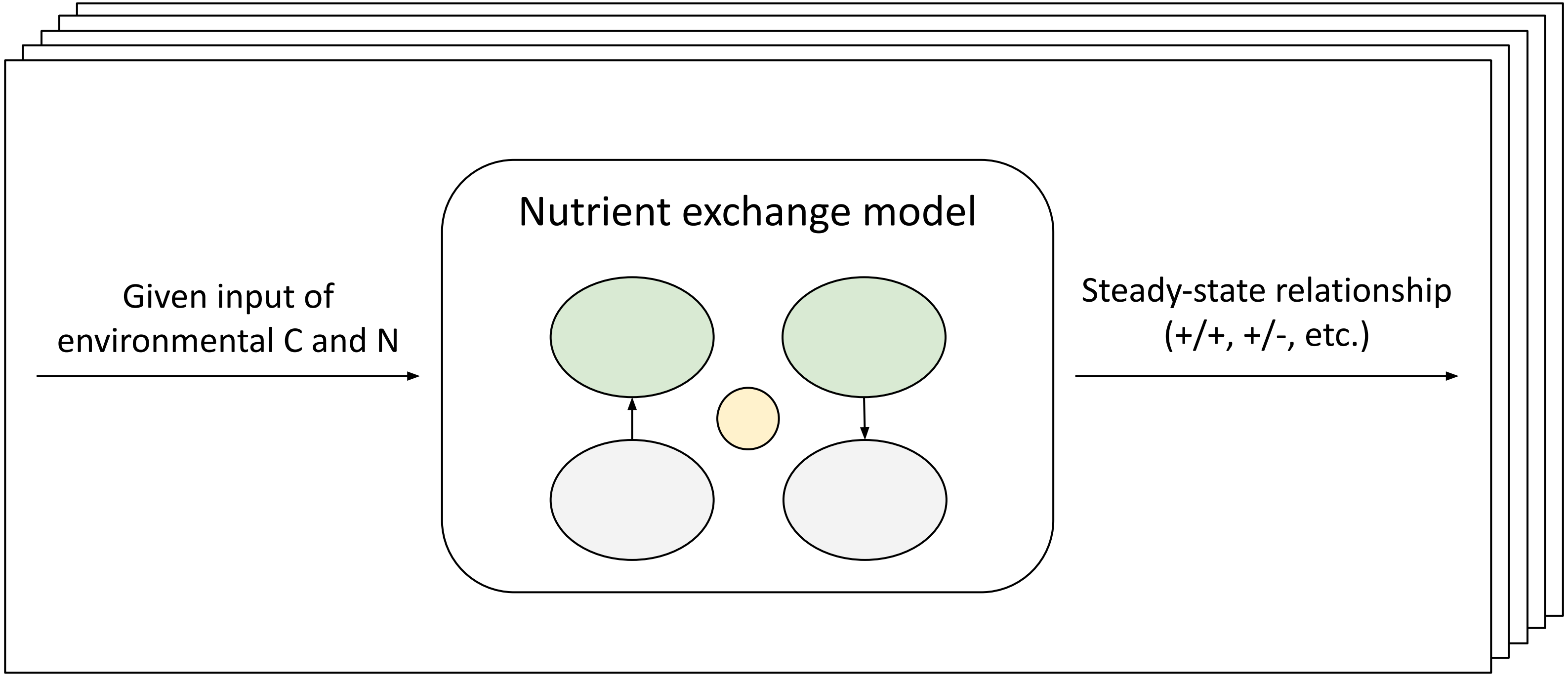
$$\frac{dN_T(t)}{dt} = \mu - kN_T(t) + M(t)N_F(t)\frac{C_{Fmin}}{C_F(t)} \quad \text{(Eq. 3)}$$

$$\frac{dC_F(t)}{dt} = \beta - kC_F(t) + M(t)C_T(t)\frac{N_{Tmin}}{N_T(t)} \quad \text{(Eq. 4)}$$

$$\frac{dM(t)}{dt} = \frac{C_{Fmin}}{C_F(t)}M(t)(1 - M(t)) - \delta M(t) \quad \text{(Eq. 5)}$$

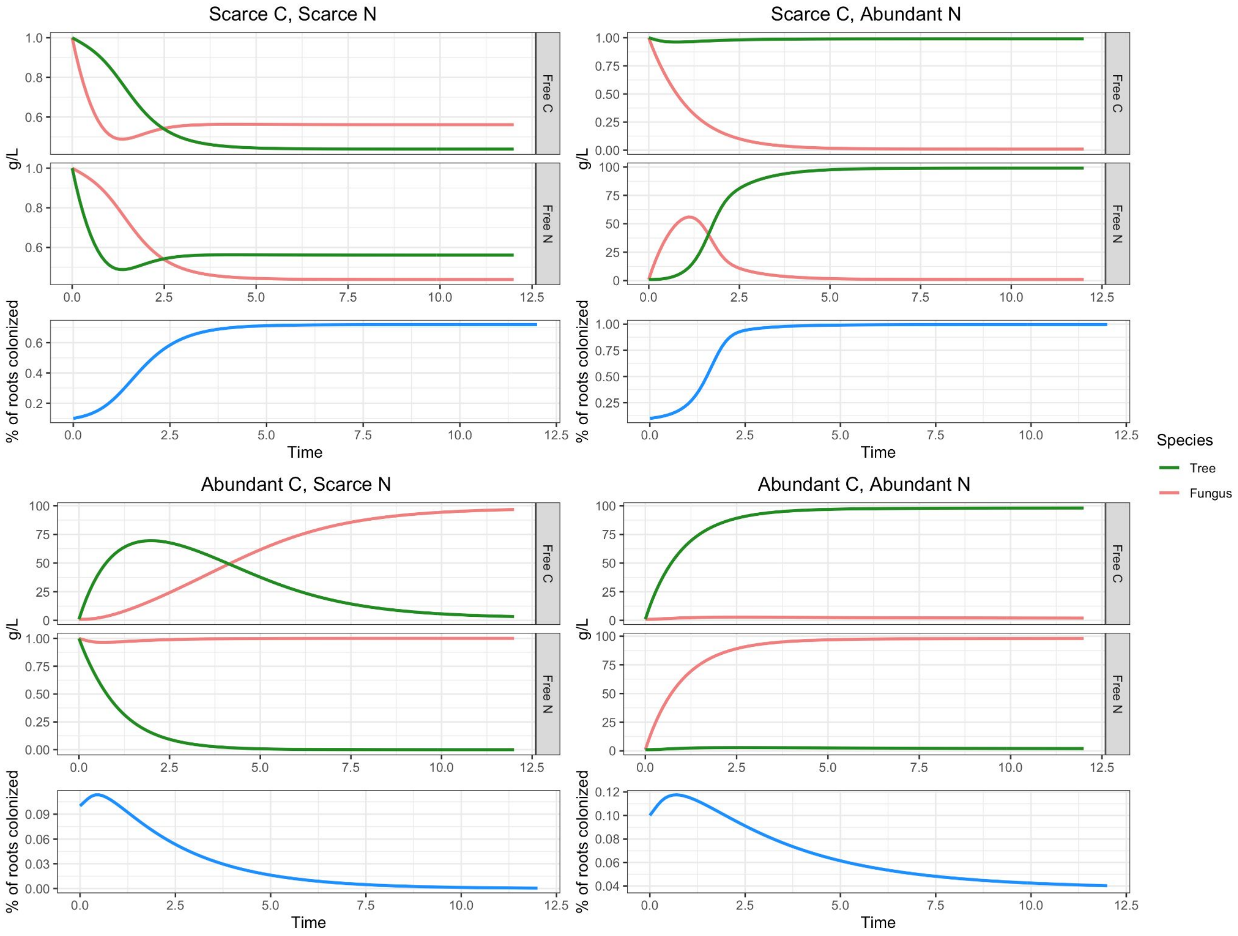
- Deterministic model in continuous time
- State variables represent free C and N available

Methods used to determine conditions for mutualism

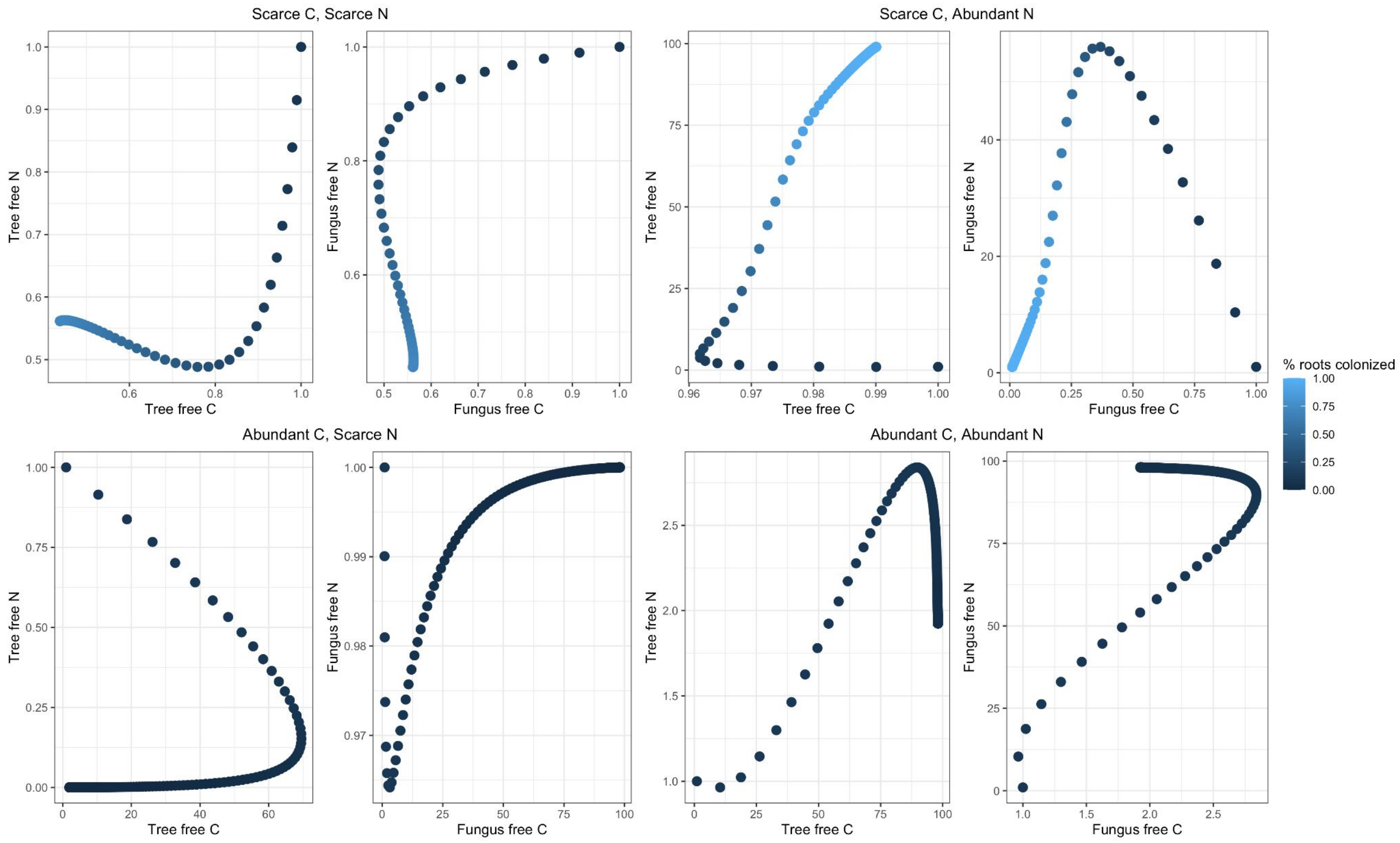


Repeated for many
variations of input C and N

Nutrient dynamics in extreme cases

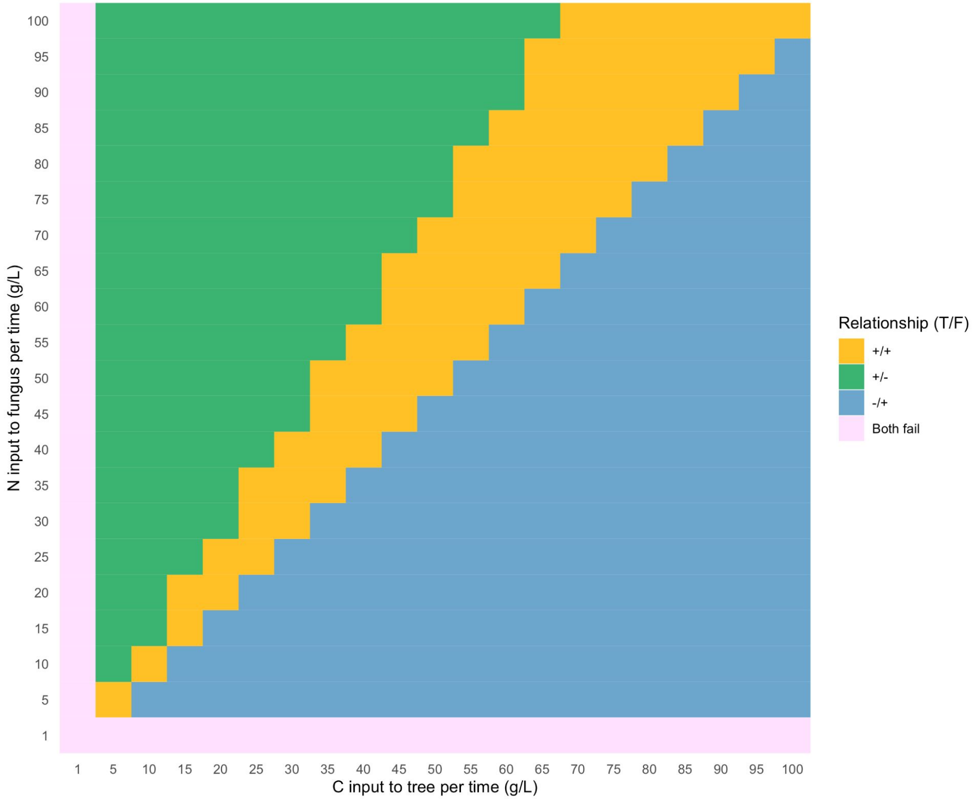


Nutrient dynamics in extreme cases



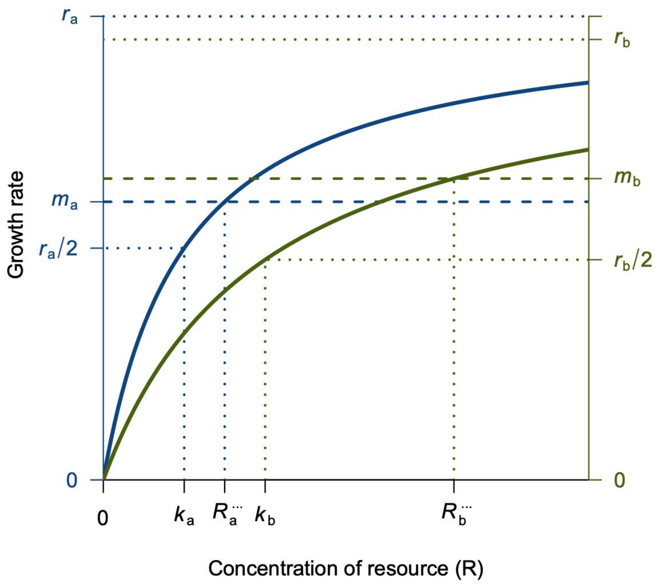
Relatively equal amounts of environmental C and N lead to mutualism

- Healthy organism = steady state C and N are both above initial values
- Mutualism (+/+): both organisms are healthy
- Parasitism (+/- or -/+): one is healthy, the other unhealthy
- Both fail: both are unhealthy



R* theory validates model mechanics

- R* theory concerns two species competing for a common resource
  - Here, tree and fungus compete for two common resources: C and N
- Species-specific R* value = environmental resource amount that puts the population at equilibrium
- R* theory: as resource availability decreases, the species with the *lower* R* value will dominate
  - Due to model structure, tree has a lower R* for C, fungus has a lower R* for N



Park, *UGA Ecology 4000* 2018

Conclusions & future directions

- My results indicate that relatively equal amounts of environmental C and N give rise to mutualism
- When one nutrient is scarce, the organism with direct access to the scarce nutrient dominates (R* theory)
- These results demonstrate the ecological balance required to maintain integral relationships, and could inform healthy forest management
- Model extensions:
  - Relax assumption that both organisms fully depend on the other for their non-specialty nutrient
  - Fit to data measured in the field