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Theory of microbial coexistence in promoting soil–plant ecosystem health

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Niche difference (ND) and fitness difference (FD)

(1) based on Lotka-Volterra competition model (Chesson, 2000, 2013)

$$ND = 1 - \rho = 1 - \frac{\sqrt{\alpha_{ij} \times \alpha_{ji}}}{\sqrt{\alpha_{jj} \times \alpha_{ii}}}$$

$$FD = \frac{f_j}{f_i} = \frac{\sqrt{\alpha_{ii} \times \alpha_{ij}}}{\sqrt{\alpha_{jj} \times \alpha_{ji}}}$$

where α_{ij} describes the per capita effect of species j on species i .

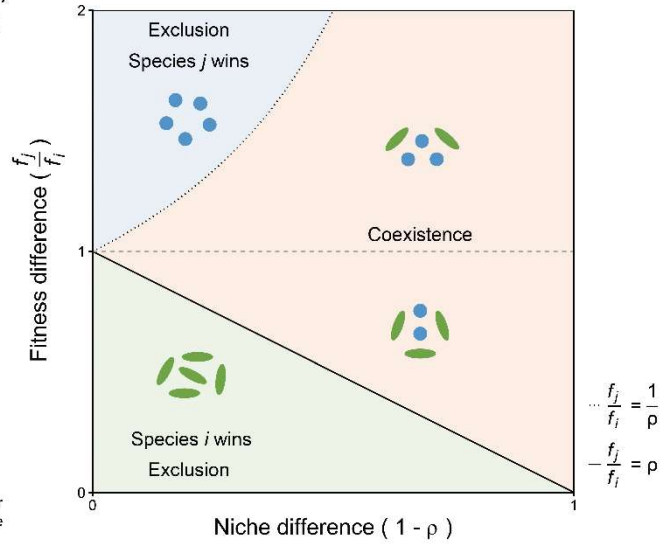
(2) based on MacArthur's consumer-resource model (Carroll et al., 2011)

$$S_i = \frac{\mu_{i,0} - \mu_{i,j}}{\mu_{i,0}}$$

$$ND = 1 - \prod_{i=1}^n S_i^{1/n}$$

$$FD = \exp \left[\left((\ln S)^2 - (\ln S)^2 \right)^{1/2} \right]$$

S_i is the sensitivity to competition, where $\mu_{i,0}$ and $\mu_{i,j}$ is the per capita growth rate of invader i in the absence and presence of the native species j respectively.



1

2 **Figure 1** The conceptual diagram of modern coexistence theory. The competitive

3 outcome is determined by the balance between niche difference (ND) and fitness

4 difference (FD), which can be calculated based on the Lotka-Volterra competition

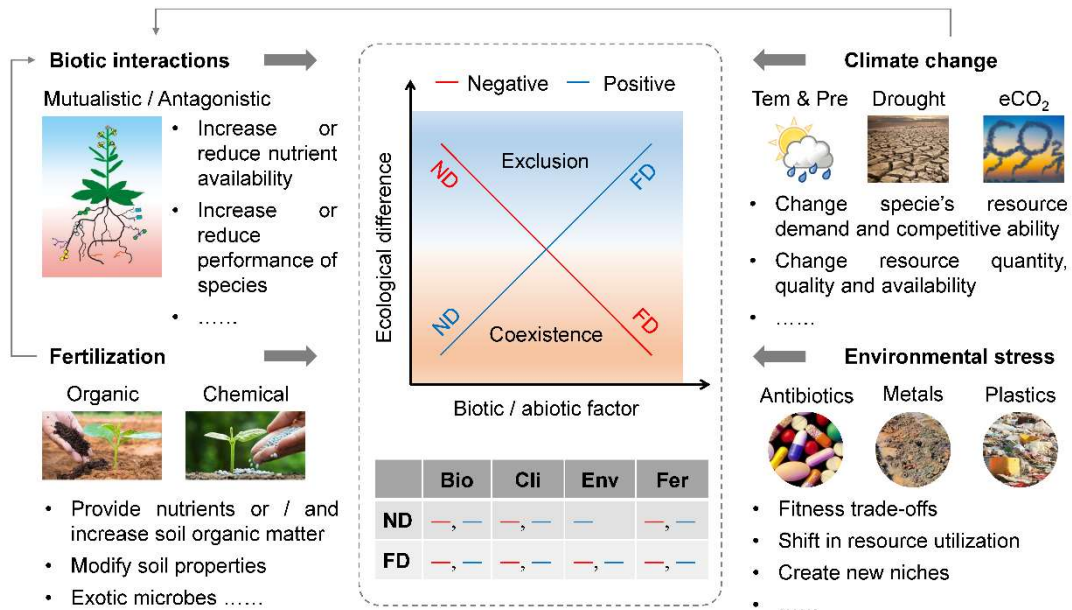
5 model (Chesson, 2000, 2013) or MacArthur's consumer-resource model (Carroll et

6 al., 2011). The dotted and solid lines represent the boundaries where f_j/f_i equals $1/\rho$

7 or ρ , respectively. The right area indicates the region where coexistence occurs; the

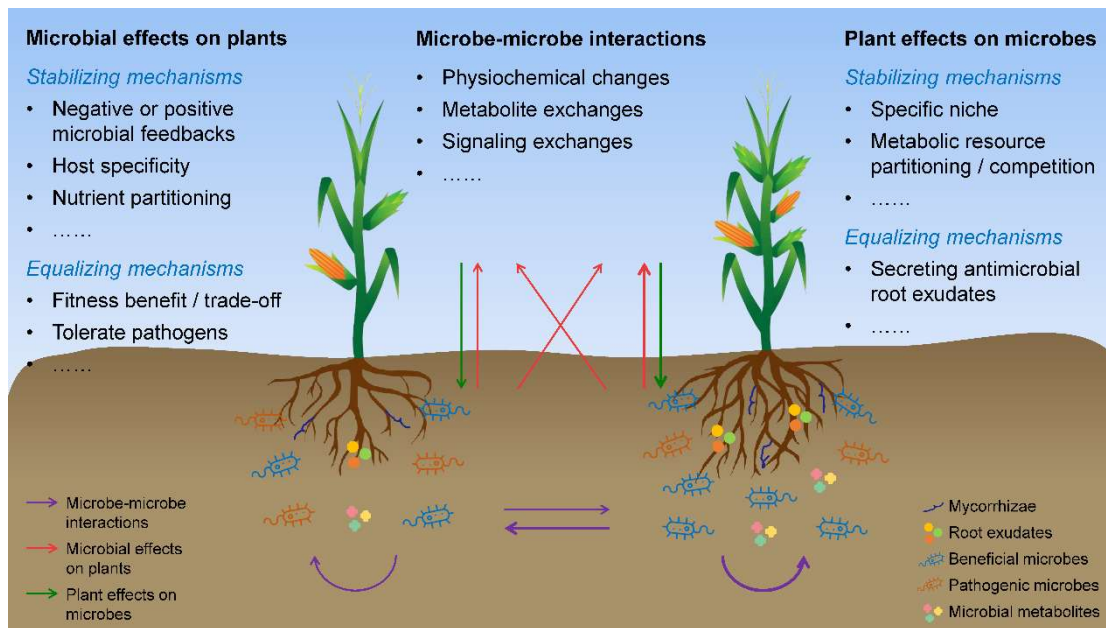
8 top and bottom areas indicate where species j or i is dominant, respectively. Figure

9 modified from Ke and Letten (Ke and Letten, 2018).



10

11 **Figure 2** Graphical presentation of possible effects of biotic and abiotic factors on
 12 niche and fitness differences. ND: niche difference; FD: fitness difference. Bio: biotic
 13 interactions; Cli: climate change; Env: environmental stress; Fer: fertilization. Red
 14 and blue lines indicate negative and positive relationships, respectively. Gray thin
 15 arrows indicate indirect impact pathways.



16

17 **Figure 3** Schematic illustrating soil microbe-microbe interactions and plant-microbe
 18 interactions through modern coexistence theory. The conceptual model of microbe-
 19 microbe interactions and plant-microbe interactions is modified after Bever's model
 20 of pairwise plant-soil feedback and its derived framework (Bever et al., 1997; Bever,
 21 2003; Kandlikar et al., 2019; Ke and Wan, 2019). The interactions among microbes
 22 can be mutualistic or antagonistic. Microbial effects on plants and plant effects on mi-
 23 crobes can be positive or negative.