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Supplemental Information

Critical Transitions in Plant-Pollinator Systems Induced by Positive Inbreeding-Reward-Pollinator Feedbacks

Heng Huang and Paolo D'Odorico

Transparent Methods

We model plant-pollinator dynamics considering the case of simple systems with low plant and pollinator diversity, such as those found in arid landscapes or areas affected by strong biodiversity losses. In these systems plant-pollinator dynamics can be modeled considering - for the purposes of this study - only two state variables accounting for plant density (G) and pollinator density (P). Despite the obvious limitations in this coarse representation of plant-pollinator systems (see discussion section), this approach lends itself to an analysis of the extent to which critical transitions could emerge in plant-pollinator dynamics as a result of resource deficiency or disturbance intensification in the presence of positive plant-pollinator feedbacks. We model the change rate in plant density (G) using the logistic growth equation

$$\frac{\mathrm{d}G}{\mathrm{d}t} = \alpha G\left(K_{\mathrm{G}} - G\right), \tag{1}$$

where α is the intrinsic population growth rate and K_{G} is the carrying capacity. K_{G} reflects the maximum population density and is constrained by environmental resources such as soil water availability in the case of water-limited ecosystems. Therefore, we assume that K_{G} varies with different resource levels and is considered as a variable in the model. Both G and K_{G} are normalized with respect to the maximum value of the carrying capacity such that they both range from 0 to 1.

Many plant species rely on a combination of selfing and outcrossing for reproduction and tend to have a higher probability of outcrossing with respect to selfing under favorable environmental conditions due to inbreeding depression (Charlesworth and Charlesworth, 1987). Therefore, following Morgan et al. (2005), α can be expressed as

$$\alpha = \theta\left(w_s S\left(G\right) + T\left(G\right)\right), \tag{2}$$

where θ is the production rate of ovules fertilized through selfing with rate $S(G)$ and outcrossing with rate $T(G)$, w_s represents the reduced success of seed production through selfing compared with outcrossing. Following previous studies (Lloyd, 1979; Morgan et al., 2005), the rate of selfing and outcrossing can be expressed as

$$S(G)=b+(1-b)\left[V(G)g(G)\right], \tag{3a}$$

$$T(G)=(1-b)V(G)\left(1-g(G)\right), \tag{3b}$$

where b is the rate of autonomous selfing in the absence of pollinators, and $V(G)$ is the visitation rate of pollinators and $g(G)$ is the fraction of pollinator-induced self-fertilization. $V(G)$ depends on population density of pollinators P (Morgan et al., 2005), which can be modeled as

$$V(G)=1-e^{-P}. \tag{4}$$

It is expected that pollinator-induced selfing will decrease with plant population density because pollinators prefer to visit different plant individuals at higher plant density and achieve optimal foraging strategies (Morgan et al., 2005). Therefore

$$g(G)=g_0e^{-rG}, \tag{5}$$

where g_0 is pollinator-induced selfing when population density is very low and r is a constant determining the rate at which pollinator-induced selfing decreases with plant density. Thus Equation (1) can be rewritten as

$$\frac{\mathrm{d}(G)}{\mathrm{d}t}=\theta\left(w_sS(G)+T(G)\right)G\left(K_G-G\right)-cG, \tag{6}$$

where we have included a linear loss term (with rate c) to account for the effect of natural or anthropogenic disturbance that acts as an external driver in our model. Here we assume that disturbance reduces plant biomass which may further result in the increased selfing probability and decreased pollinator visitation.

The high nestedness of plant-pollinator mutualistic networks has been widely recognized (Bascompte et al., 2003; Suweis et al., 2013), suggesting that plant species pollinated by generalists are more likely to be specialists (Aizen and Harder, 2007). The study of complex plant-pollinator dynamics has shown the existence of important thresholds and critical transitions associated with their mutualistic ecological networks. Here we focus on the effect of positive feedbacks in plant-pollinator dynamics and their ability to induce alternative stable states and critical transitions independently of the complexity of their mutualistic networks. To this end, we consider a simplified system in which there is only one plant species serving as forage source for pollinators in the system. In other words, pollinator dynamics are highly dependent on the abundance of that plant species. This assumption allows us to simplify the modelling of the concurrent dynamics of pollinators. Additionally, it provides important insights into the conditions explaining ecological stability of specialized plant-pollinator systems under global change since specialist pollinator species are more vulnerable than generalists and are declining across the world (Potts et al., 2010). The pollination dynamics can be expressed similarly as

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \sigma P\left(K_{\mathrm{P}} - P\right) - kP, \tag{7}$$

where P is the pollinator density, σ is the intrinsic growth rate of pollinator population and K_{P} is the maximum pollinator density that can be reached and k is the pollinator mortality rate caused directly by disturbances such as habitat loss and pesticide. We assume that K_{P} is a function of G and $g(G)$ because both plant population density and selfing rate can affect the quantity and quality of floral rewards and therefore the pollinator dynamics

$$K_{\mathrm{P}} = G\left[1 - g\left(G\right)\right]. \tag{8}$$

In other words, because pollinators such as bees feed on floral resources such as pollen and nectar, their carrying capacity increases with plant density (more plants produce more floral rewards) but decreases with increasing selfing fractions because selfing reduces the pollen quantity and quality in the sense that pollen and nectar become less nutritious (Griffin and Eckert, 2003; Aizen and Harder, 2007). Notice that in Equation (7) K_P is normalized between 0 and 1, P is the normalized pollinator density ranging between 0 and 1.

We parameterize the model and show whether changes in resource availability and intensity of disturbance can cause a non-linear shift in plant and pollinator populations. According to Morgan et al. (2005), we set $\theta = 1$, $w_s = 0.6$, $b = 0.05$, $g_0 = 1$, $r = 1$, and $\sigma = 1$. We note that the model can be applied to different ecosystems given the generality of the inbreeding-reward-pollinator feedbacks.

Supplemental References

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