Evolution Arrests Invasions of Cooperative Populations

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Population expansions trigger many biomedical and ecological transitions, from tumor growth to invasions of non-native species. Although population spreading often selects for more invasive phenotypes, we show that this outcome is far from inevitable. In cooperative populations, mutations reducing dispersal have a competitive advantage. Such mutations then steadily accumulate at the expansion front, bringing invasion to a halt. Our findings are a rare example of evolution driving the population into an unfavorable state, and they could lead to new strategies to combat unwelcome invaders.

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Locust swarms, cancer metastasis, and epidemics are some feared examples of spatial invasions. Spatial spreading is the only mechanism for a species to become highly abundant, whether we are considering a bacterial colony growing on a Petri dish [1,2] or the human expansion across the globe [3]. Many invasions are unwelcome because they threaten biodiversity [4], agriculture [5], or human health [6]. Unfortunately, efforts to control or slow down invaders often fail in part because they become more invasive over time [7]. The evolution of invasive traits and invasion acceleration has been repeatedly observed in nature, from the takeover of Australia by cane toads [8] to the progression of human cancers [9,10].

Selection for faster dispersal makes sense because it increases the rate of invasion and allows early colonizers to access new territories with untapped resources. A large body of theoretical [11–13] and experimental work [7,8,14] supports this intuition in populations that grow noncooperatively, i.e., when a very small number of organisms is sufficient to establish a viable population. However, many populations, including cancer tumors [9,10,15–17], do grow cooperatively, a phenomenon known in ecology as the Allee effect [18]. In fact, cooperatively growing populations can even become extinct when the population density falls below a critical value, termed the Allee threshold [19,20]. We find that the intuitive picture of "the survival of the fastest" fails for such populations, and natural selection can in fact favor mutants with lower dispersal rates. Over time, repeated selection for lower dispersal leads to a complete arrest of the spatial invasion.

To understand when invasions accelerate and when they come to a halt, we analyzed a commonly used mathematical model for population dynamics that can be tuned from noncooperative to cooperative growth by changing a single parameter. We considered the competition between two genotypes with different dispersal abilities and computed their relative fitness analytically. Our main result is that selection favors slower dispersal for a substantial region of the parameter space where the Allee threshold is sufficiently high. Numerical simulations confirmed that evolution in such populations gradually reduces dispersal and eventually stops the invasion, even when multiple mutants could compete simultaneously and other model assumptions were relaxed.

Selective pressure on the dispersal rate can be understood most readily from the competition of two types (mutants, strains, or species) with different dispersal abilities as they invade new territory. For simplicity, we focus on short-range dispersal that can be described by effective diffusion, and we only consider the dynamics in the direction of spreading. Mathematically, the model is expressed as

$$\frac{\partial c_1}{\partial t} = D_1 \frac{\partial^2 c_1}{\partial x^2} + c_1 g(c), \quad \frac{\partial c_2}{\partial t} = D_2 \frac{\partial^2 c_2}{\partial x^2} + c_2 g(c), \quad (1)$$

where c_1 and c_2 are the population densities of the two types that depend on time t and spatial position x, D_1 and D_2 are their dispersal rates, and $g(c)$ is the density-dependent per capita growth rate. We assume that $g(c)$ is the same for the two types and depends only on the total population density $c = c_1 + c_2$. Since slower-dispersing types often grow faster because of the commonly observed trade-off between dispersal and growth, our results put a lower bound on the fitness advantage of the type dispersing more slowly. In the Supplemental Material, our analysis is further generalized to account for the different growth rates of the types [21].

For $g(c)$, we assume the following functional form, which has been extensively used in the literature [12,18,33,34] because it allows one to easily tune the degree of cooperation in population dynamics from purely competitive to highly cooperative growth:

$$g(c) = r(K - c)(c - c^*)/K^2. \quad (2)$$

Here, r sets the time scale of growth, K is the carrying capacity, i.e., the maximal population density that can be sustained by the habitat, and c^* is a parameter that determines the degree of cooperation, which is known as the Allee threshold. For $c^* < -K$, the types grow

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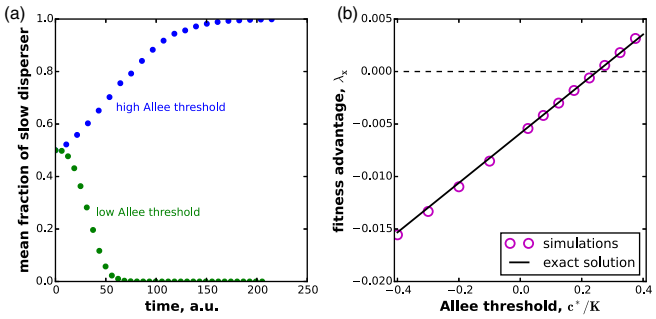

FIG. 1 (color online). The effects of cooperative growth on the evolution of dispersal during invasion. (a) Simulations of the competition between a slow ($D_1 = 0.5$) and a fast ($D_2 = 1$) disperser during a spatial expansion. The fraction of the slower disperser decreases in populations with a low Allee threshold ($c^* = 0.2$), but increases in populations with a high Allee threshold ($c^* = 0.35$). (b) The fitness advantage of the slower disperser ($D_1/D_2 = 0.95$) changes from negative (deleterious) to positive (beneficial) as the Allee threshold is increased. In simulations, we never observed the coexistence of the two types; instead, extinction is observed for the types that are deleterious when rare ($\lambda < 0$), and complete fixation is observed for the types that are beneficial when rare ($\lambda > 0$).

noncooperatively because $g(c)$ monotonically decreases from its maximal value at low population densities to zero when the population is at the carrying capacity and interspecific competition prevents further growth. Population grows cooperatively for higher values of c^* because the per capita growth rate reaches a maximum at nonzero density that strikes the balance between interspecific competition and facilitation. For $c^* > 0$, the effects of cooperative growth become particularly pronounced. Indeed, the growth rate is negative for $c < c^*$ and, therefore, small populations are not viable. Such dynamics, known as the strong Allee effect, arise because a critical number of individuals is necessary for a sufficient level of cooperation [10,18].

We first tested whether unequal dispersal rates lead to fitness differences between the two types by solving Eq. (1) numerically (see Supplemental Material [21]). When population growth was noncooperative, we found that the faster-dispersing species have a competitive advantage in agreement with the current theory [7,11,13]. Quite unexpectedly, the opposite outcome was observed for strongly cooperative growth: The type with the lower dispersal rate became dominant at the expansion front and eventually took over the population [Fig. 1(a)].

To understand this counterintuitive dynamics, we examined how the relative fitness of the two types depends on the magnitude of the Allee threshold c^*. In the context of spatial expansions, there are two complementary ways to quantify the fitness advantage of a mutant. The first measure, λ, is the exponential growth rate of the mutant, similar to what is commonly done for populations that are not expanding; a negative λ corresponds to decay, not growth. The second measure, λ_x, is the growth rate of the mutant not in units of time, but rather in units of distance traveled by the expansion. The two measures are related by $\lambda = \lambda_x v$, where v is the expansion velocity. The advantage of the second measure is that it can be applied in situations when the spatial distribution of the genotypes is available for only a single time point. We were able to compute both fitness measures analytically. The complete details of this calculation are given in the Supplemental Material [21], but our approach is briefly summarized below.

When a mutant first appears, its abundance is too small to immediately influence the course of the range expansion; therefore, we can study the dynamics of the mutant fraction in the reference frame comoving with the expansion, effectively reducing the two coupled equations in Eq. (1) to a single equation. This remaining equation has the form of a Fokker-Planck equation with a source term, and its largest eigenvalue determines whether the total fraction of the mutant will increase or decrease with time. We were able to obtain this largest eigenvalue and the corresponding eigenfunction exactly in terms of only elementary functions. For small differences in the dispersal abilities $|D_1 - D_2| \ll D_2$, our result takes a particularly simple form,

$$\lambda_x = \frac{D_1 - D_2}{6D_2}\sqrt{\frac{r}{2D_2}}\left(1 - 4\frac{c^*}{K}\right), \tag{3}$$

which is valid for $c^* > -K/2$; see Supplemental Material for $c^* < -K/2$ [21]. Thus, λ_x is a linear function of the Allee threshold c^*, which changes sign at $c^* = K/4$. For low Allee thresholds, natural selection favors mutants with higher dispersal; however, when growth is highly cooperative, the direction of selection is reversed and slower dispersers are favored. Numerical simulations of Eq. (1) are in excellent agreement with our exact solution [Fig. 1(b)]. In the Supplemental Material, we explain that the direction of natural selection remains the same as the mutant takes over the population, and we further discuss the effects of mutations and demographic fluctuations by connecting the largest eigenvalue to the fixation probability of the mutant [21].

Our finding that lower dispersal is advantageous seems counterintuitive. Indeed, a mutant unable to disperse cannot possibly take over the expansion front. The resolution of this apparent paradox is that Eq. (3) is only valid for $D_1 \approx D_2$, and the direction of natural selection changes as D_1 approaches zero. The exact expression for the selective advantage for arbitrary D_1/D_2 is given in the Supplemental Material [21] and is plotted in Fig. 2 for different values of the Allee threshold. When the Allee effect is absent or weak, selection unconditionally selects for faster dispersal [Fig. 2(a)], but as the Allee threshold increases and becomes positive, mutants with very large dispersal rates become less fit than the wild type [Fig. 2(b)]. This is expected because mutants that disperse too far ahead of the front cannot reach the critical density necessary to establish a viable population. As a result, there is an optimal improvement in dispersal abilities that is favored by natural

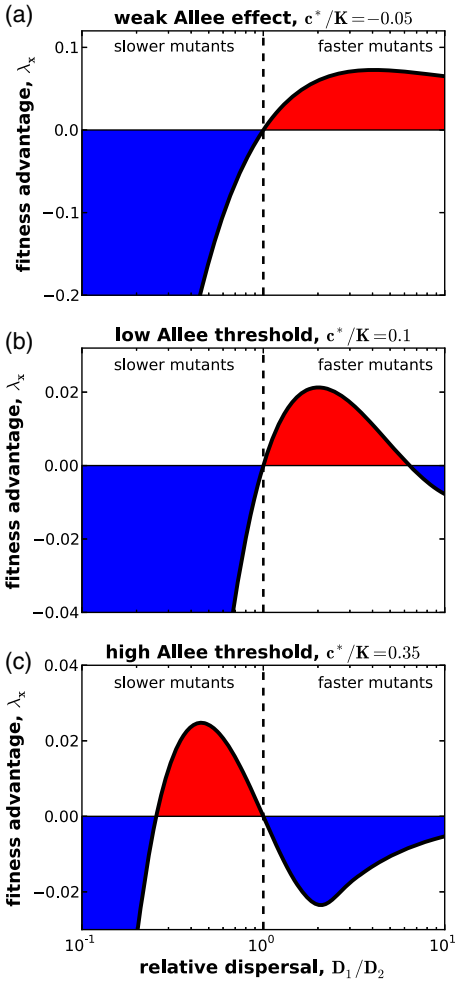

FIG. 2 (color online). Allee effect determines how fitness depends on dispersal. (a) Faster dispersers are unconditionally favored when the Allee effect is weak. Note that the fitness advantage reaches a maximum at a finite D_1/D_2. (b) When the Allee effect is strong, but the Allee threshold is low, selection still favors faster dispersal. Very fast mutants, however, are at a disadvantage. (c) For high Allee threshold, only slower-dispersing mutants can succeed, but mutants that disperse too slowly are selected against. In all panels, the exact solution is plotted, and colors highlight beneficial (red) and deleterious (blue) mutations. The dashed line marks $D_1 = D_2$, where both types have the same fitness. Near this point, the fitness advantage of type 1 in the background of type 2 equals the fitness disadvantage of type 2 in the background of type 1, but this symmetry breaks down when the dispersal rates of the types are very different; see Supplemental Material [21]. Nevertheless, the exchange of D_1 and D_2 always converts a beneficial mutant to a deleterious one. In consequence, a mutation that is beneficial when rare will remain beneficial when it approaches fixation, indicating that the direction of natural selection is the same for small and large f.

selection. In contrast, when the Allee effect is sufficiently strong, only reduced dispersal is advantageous [Fig. 2(c)]. Again, there is an optimal reduction in the dispersal rate that results in the highest fitness advantage, and mutants that disperse too slowly are outcompeted by the wild type.

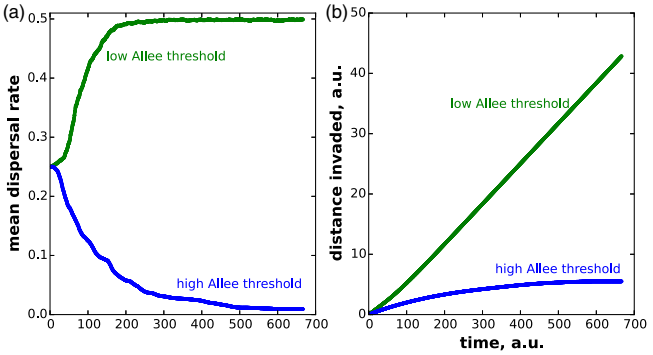

FIG. 3 (color online). When the rate of dispersal is allowed to evolve, simulations show that invasions can both accelerate and decelerate depending on the strength of an Allee effect. (a) The mean dispersal rate increases to its maximally allowed value when the Allee threshold is low (green), but the dispersal rate decreases to zero when the Allee threshold is high (blue). (b) For the same simulations as in (a), we plot the extent of spatial spread by the populations. Invasions with a low Allee threshold ($c^*/K = 0.2$) accelerate, while invasions with a high Allee threshold ($c^*/K = 0.35$) come to a standstill.

Although natural selection typically eliminates the mutants that either increase or decrease the dispersal rate by a large amount, sequential fixation of mutations could lead to a substantial change in the expansion velocity. Indeed, our results show that the fitness advantage of the mutant depends on the relative, rather than absolute, change in the dispersal ability. Thus, if the Allee effect is strong enough to favor slower mutants, then mutants that reduce the dispersal rate even further will become advantageous once the takeover by the original mutant is complete. We then expect that the repeated cycle of dispersal reduction will eventually bring the invasion to a standstill. The opposite behavior is expected when the Allee threshold is low.

To test these predictions, we performed computer simulations that relax many of the assumptions underlying Eq. (1), as described in the Supplemental Material [21]. In particular, we incorporated the stochastic fluctuations due to genetic drift and allowed multiple mutations modifying the dispersal rate to arise and compete at the same time. Shown in Fig. 3, simulations display a steady decline in the dispersal ability and expansion arrest for strongly cooperative growth. Consistent with previous studies [7,11–13], dispersal rates increase and the rate of invasion accelerates when the Allee threshold is low.

Natural selection on dispersal has been extensively studied, and many factors that favor faster or slower dispersal have been identified [35–37]. Fast dispersers can avoid inbreeding depression, escape competition, or find a suitable habitat. At the same time, dispersal diverts resources from reproduction and survival, increases predation, and can place organisms in inhospitable environments. In the context of range expansions, however, high dispersal seems unambiguously beneficial because early colonizers get a disproportionate advantage. Yet, we

showed that spatial expansions can select for mutants with lower dispersal rates. Continuous reduction of dispersal rates then slows down, and eventually stops, further invasion. Invasion arrest requires strong cooperative growth and is in stark contrast to the dynamics in noncooperative populations, where spatial expansions select for higher dispersal.

We expect that our results are robust to the specific assumptions made in this study such as the diffusionlike dispersal and the specific form of the growth function because, at its core, our analysis relies on very general arguments (Supplemental Material [21]). Indeed, we argue that faster mutants get ahead at low or negative Allee thresholds because they can successfully grow at the front and effectively establish secondary invasions; in contrast, these dynamics do not occur at high Allee thresholds because faster dispersers arrive at low-density regions that cannot sustain growth.

At a very high level, our result can be understood as the emergence of cheating in a cooperatively growing population. Cheating is a behavior that benefits the individuals, but is detrimental to the population as a whole [38]. One well-studied example is consuming, but not contributing, to a common resource (public good), a behavior typical of both humans [39–41] and microbes [38,42,43]. In the context of population spreading, high dispersal can be viewed as an effective public good because it creates high densities in the outer edge of the expansion front, thereby increasing the survival of new immigrants to that region. Although high population densities benefit both slow and fast dispersers equally, the latter pay a much higher cost for producing this public good. Indeed, faster dispersers are more likely to suffer higher death rates at the low-density invasion front, where they arrive more frequently. As a result, "cheating" by the slow dispersers is the reason for their selective advantage.

In addition to the classical emergence of cheating, expansion arrest is an example of evolution driving a population to a less adapted state. Our ability to exploit or trigger such counterproductive evolution may be important in managing invasive species and agricultural pests, or even cancer tumors. Concretely, our results open up new opportunities to control biological invasions. Instead of trying to destroy the invader, a better strategy could be to elevate the minimal density required for growth (the Allee threshold) to a level necessary for evolution to select for invasion arrest. Such strategies could have important advantages over the traditional approaches. Increasing the Allee threshold in cancer tumors could overcome the emergence of drug resistance because the bulk of the tumor is at a high density and is not affected by the treatment. Similarly, resistance should emerge much more slowly in agricultural pests.

Although the manipulation of Allee thresholds is a relatively unexplored and potentially difficult endeavor, some management programs have been successful at increasing the Allee effects in the European gypsy moth, one of the most expensive pests in the United States [44–47]. These moths suffer from a strong Allee effect because they struggle to find mates at low population densities [47]. Recent management programs exacerbated this Allee effect by spreading artificial pheromones that disorient male moths and prevent them from finding female mates, thereby effectively eradicating low-density populations [44–46]. European gypsy moths and other pests with similarly strong Allee effects could be close to the critical Allee threshold necessary for the invasion arrest. In such populations, further increase of the Allee effect could be more feasible and effective than reducing the carrying capacity.

Beyond ecology, our results could also find applications in other areas of science such as chemical kinetics, where reaction-diffusion equations are often used. Quite broadly, we find that a variation in the motility of agents can have completely opposite effects on their dynamics, depending on the reaction kinetics at the expansion front.

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[1] K. S. Korolev, M. J. Muller, N. Karahan, A. W. Murray, O. Hallatschek, and D. R. Nelson, Selective sweeps in growing microbial colonies, Phys. Biol. **9**, 026008 (2012).
[2] J. Wakita, K. Komatsu, A. Nakahara, T. Matsuyama, and M. Matsushita, Experimental investigation on the validity of population dynamics approach to bacterial colony formation, J. Phys. Soc. Jpn. **63**, 1205 (1994).
[3] A. Templeton, Out of Africa again and again, Nature (London) **416**, 45 (2002).
[4] D. U. Hooper, E. C. Adair, B. J. Cardinale, J. E. K. Byrnes, B. A. Hungate, K. L. Matulich, A. Gonzalez, J. E. Duffy, L. Gamfeldt, and M. I. O'Connor, A global synthesis reveals biodiversity loss as a major driver of ecosystem change, Nature **486**, 105 (2012).
[5] M. E. Gray, T. W. Sappington, N. J. Miller, J. Moeser, and M. O. Bohn, Adaptation and invasiveness of western corn rootworm: Intensifying research on a worsening pest, Annu. Rev. Entomol. **54**, 303 (2009).
[6] D. Brockmann and D. Helbing, The hidden geometry of complex, network-driven contagion phenomena, Science **342**, 1337 (2013).
[7] C. D. Thomas, E. J. Bodsworth, R. J. Wilson, A. D. Simmons, Z. G. Davies, M. Musche, and L. Conradt, Ecological and evolutionary processes at expanding range margins, Nature (London) **411**, 577 (2001).
[8] B. L. Phillips, G. P. Brown, J. K. Webb, and R. Shine, Invasion and the evolution of speed in toads, Nature (London) **439**, 803 (2006).
[9] L. M. F. Merlo, J. W. Pepper, B. J. Reid, and C. C. Maley, Cancer as an evolutionary and ecological process, Nat. Rev. Cancer **6**, 924 (2006).

[10] K. S. Korolev, J. B. Xavier, and J. Gore, Turning ecology and evolution against cancer, Nat. Rev. Cancer **14**, 371 (2014).
[11] R. Shine, G. P. Brown, and B. L. Phillips, An evolutionary process that assembles phenotypes through space rather than through time, Proc. Natl. Acad. Sci. U.S.A. **108**, 5708 (2011).
[12] K. S. Korolev, The fate of cooperation during range expansions, PLoS Comput. Biol. **9**, e1002994 (2013).
[13] O. Benichou, V. Calvez, N. Meunier, and R. Voituriez, Front acceleration by dynamic selection in Fisher population waves, Phys. Rev. E **86**, 041908 (2012).
[14] D. van Ditmarsch, K. E. Boyle, H. Sakhtah, J. E. Oyler, C. D. Nadell, E. Deziel, L. E. Dietrich, and J. B. Xavier, Convergent evolution of hyperswarming leads to impaired biofilm formation in pathogenic bacteria, Cell Rep. **4**, 697 (2013).
[15] L. Berec, E. Angulo, and F. Courchamp, Multiple Allee effects and population management, Trends Ecol. Evol. **22**, 185 (2007).
[16] T. H. Clutton Brock, D. Gaynor, G. M. McIlrath, A. Maccoll, R. Kansky, P. Chadwick, M. Manser, J. D. Skinner, and P. Brotherton, Predation, group size and mortality in a cooperative mongoose, Suricata suricatta, J. Anim. Ecol. **68**, 672 (1999).
[17] A. S. Cleary, T. L. Leonard, S. A. Gestl, and E. J. Gunther, Tumour cell heterogeneity maintained by cooperating subclones in Wnt-driven mammary cancers, Nature (London) **508**, 113 (2014).
[18] F. Courchamp, T. Clutton-Brock, and B. Grenfell, Inverse density dependence and the Allee effect, Trends Ecol. Evol. **14**, 405 (1999).
[19] M. Scheffer, J. Bascompte, W. A. Brock, V. Brovkin, S. R. Carpenter, V. Dakos, H. Held, E. H. van Nes, M. Rietkerk, and G. Sugihara, Early-warning signals for critical transitions, Nature (London) **461**, 53 (2009).
[20] L. Dai, D. Vorselen, K. S. Korolev, and J. Gore, Generic indicators for loss of resilience before a tipping point leading to population collapse, Science **336**, 1175 (2012).
[21] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.115.208104 for technical details and further discussion, which includes Refs. [22–32].
[22] J. H. Gillespie, *Population Genetics: A Concise Guide* (JHU Press, Baltimore, London, 2004).
[23] R. A. Fisher, The wave of advance of advantageous genes, Ann. Eugen. **7**, 355 (1937).
[24] A. N. Kolmogorov, N. Petrovsky, and N. S. Piscounov, A study of the equation of diffusion with increase in the quantity of matter, and its application to a biological problem, Moscow Univ. Bull. Math. **1**, 1 (1937).
[25] W. Van Saarloos, Front propagation into unstable states, Phys. Rep. **386**, 29 (2003).
[26] E. Titchmarsh, *Eigenfunction Expansions Associated with Second-Order Differential Equations* (Clarendon Press, Oxford, 1946).
[27] O. Hallatschek and D. Nelson, Gene surfing in expanding populations, Theor. Popul. Biol. **73**, 158 (2008).
[28] R. Lehe, O. Hallatschek, and L. Peliti, The rate of beneficial mutations surfing on the wave of a range expansion, PLoS Comput. Biol. **8**, e1002447 (2012).
[29] D. Waxman and S. Gavrilets, 20 questions on adaptive dynamics, J. Evol. Biol. **18**, 1139 (2005).
[30] M. Kot, M. A. Lewis, and P. van den Driessche, Dispersal data and the spread of invading organisms, Ecology **77**, 2027 (1996).
[31] M. Kimura and G. H. Weiss, The stepping stone model of population structure and the decrease of genetic correlation with distance, Genetics **49**, 561 (1964).
[32] R. Levins, Some demographic and genetic consequences of environmental heterogeneity for biological control, Bulletin of the Ecological Society of America **15**, 237 (1969).
[33] D. G. Aronson and H. G. Weinberger, *Nonlinear Diffusion in Population Genetics, Combustion and Nerve Propagation*, Lectures Notes Math Vol. 446 (Springer, New York, 1975).
[34] P. C. Fife and J. B. McLeod, The approach of solutions of nonlinear diffusion equations to travelling front solutions, Arch. Ration. Mech. Anal. **65**, 335 (1977).
[35] O. Ronce, How does it feel to be like a rolling stone? Ten questions about dispersal evolution, Annu. Rev. Ecol. Evol. Syst. **65**, 231 (2007).
[36] J. Dockery, V. Hutson, K. Mischaikow, and M. Pernarowski, The evolution of slow dispersal rates: A reaction diffusion model, J. Math. Biol. **37**, 61 (1998).
[37] V. Hutson, K. Mischaikow, and P. Polavcik, The evolution of dispersal rates in a heterogeneous time-periodic environment, J. Math. Biol. **43**, 501 (2001).
[38] S. A. West, S. P. Diggle, A. Buckling, A. Gardner, and A. S. Griffin, The social lives of microbes, Annu. Rev. Ecol. Evol. Syst. **38**, 53 (2007).
[39] G. Hardin, The tragedy of the commons, Science **162**, 1243 (1968).
[40] R. Axelrod and W. D. Hamilton, The evolution of cooperation, Science **211**, 1390 (1981).
[41] A. Gardner and K. R. Foster, The evolution and ecology of cooperation–history and concepts, in *Ecology of Social Evolution*, edited by J. Korb and J. Heinze (Springer, Berlin, 2008), pp. 1–36.
[42] C. D. Nadell, J. Xavier, and K. R. Foster, The sociobiology of biofilms, FEMS Microbiol. Rev. **33**, 206 (2009).
[43] R. Menon and K. S. Korolev, Public Good Diffusion Limits Microbial Mutualism, Phys. Rev. Lett. **114**, 168102 (2015).
[44] P. C. Tobin, C. Robinet, D. M. Johnson, S. L. Whitmire, O. N. Bjørnstad, and A. M. Liebhold, The role of Allee effects in gypsy moth, Lymantria dispar (L.), invasions, Popul. Ecol. **51**, 373 (2009).
[45] P. C. Tobin, L. M. Blackburn *et al.*, Slow the spread: a national program to manage the gypsy moth, General Technical Report–Northern Research Station, USDA Forest Service, 2007.
[46] K. W. Thorpe, D. S. Leonard, V. C. Mastro, W. McLane, R. C. Reardon, P. Sellers, R. E. Webb, and S. E. Talley, Effectiveness of gypsy moth mating disruption from aerial applications of plastic laminate flakes with and without a sticking agent, Agric. For. Entomol. **2**, 225 (2000).
[47] D. M. Johnson, A. M. Liebhold, P. C. Tobin, and O. N. Bjornstad, Allee effects and pulsed invasion by the gypsy moth, Nature (London) **444**, 361 (2006).