

Minority-group incubators and majority-group reservoirs support the diffusion of climate change adaptations

Matthew A. Turner*, Alyson L. Singleton, Mallory J. Harris, Ian Harryman, Cesar Augusto Lopez, Ronan Forde Arthur, Caroline Muraida, and James Holland Jones

Stanford Doerr School of Sustainability, Social Sciences Division, Stanford University, Stanford, CA, USA

*Correspondence: maturner@stanford.edu

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Abstract

Successful climate change adaptation depends on the spread and maintenance of adaptive behaviors. Current theory suggests that the heterogeneity of metapopulation structure can help adaptations diffuse throughout a population. In this paper, we develop an agent-based model of the spread of adaptations in populations with minority-majority metapopulation structure, where subpopulations learn more or less frequently from their own group compared to the other group. In our simulations, minority-majority-structured populations with moderate degrees of in-group preference better spread and maintained an adaptation compared to populations with more equal-sized groups and weak homophily. Minority groups act as incubators for an adaptation, while majority groups act as reservoirs for an adaptation once it has spread widely. This means that adaptations diffuse throughout populations better when minority groups start out knowing an adaptation, as Indigenous populations often do, while cohesion among majority groups further promotes adaptation diffusion. Our work advances the goal of this theme issue by developing new theoretical insights and demonstrating the utility of cultural evolutionary theory and methods as important tools in the nascent science of culture that climate change adaptation needs.

1 Introduction

Climate change threatens societies worldwide [1], but often most severely affects populations least responsible for greenhouse gas emissions [2]. Help from rich countries most responsible for the emissions is unreliable [3]. To maximize the chances that climate change adaptation efforts succeed, it is critical to understand how basic social factors affect climate change adaptation outcomes. Here, we focus on how the diffusion of adaptations is affected by group structure within a *metapopulation* (i.e., a population of populations or a network characterized by strong *community structure* [4]) and how frequently individuals learn from others within one's own group versus from individuals from other groups (i.e., *homophily*). Even though anthropogenic global warming is accelerating and intensifying environmental change, local and Indigenous populations often already know of valuable adaptation strategies given that their livelihoods are directly associated with a constantly changing environment, as was the case for their ancestors [5]. Qualitative evidence suggests that existing strategies to promote climate change adaptation are most successful when local stakeholders participate, with community-based adaptation efforts being one important approach to community involvement in climate change adaptation [6]. Despite this evidence, there are open questions as to how adaptive practices spread through heterogeneous populations, which is essential to adaptation success [7]. We are particularly interested in metapopulations

characterized by minority-majority structure since this is a characteristic of many subsistence populations living on the economic periphery of more market-integrated populations [8, 9]. To understand how adaptive behaviors or practices diffuse through metapopulations, we developed an agent-based model of the spread of an adaptive behavior or practice to understand when, how, and which forms of minority-majority structure promote the diffusion of adaptations. This minority-majority group model setup is the simplest non-trivial metapopulation structure. It represents two groups where one group, the *majority group*, outnumbers the other, the *minority group*, and each group learns more or less frequently from its own group and the other group, specified by group-level homophily.

Adaptation has several meanings within climate science, but here we adopt a general definition consistent with anthropological use [10, 11] and suitable for studying the spread of culturally-learned behaviors [12], including climate change adaptation or mitigation strategies. We define an *adaptation* as a solution to a problem that confers a greater fitness to those who employ the behavior compared to those who do not [10]. We assume that the adaptation already exists, generated through some adaptive cultural process [13]. *Adaptation success* in our model, therefore, is whether or not the adaptation successfully spreads to all simulated individuals (i.e., *agents*) in the model, and not the innovation of a novel adaptation per se. This represents the cases where, for example, an adaptation is introduced by a development actor such as a local government or international development agency [6, 9]. It also may represent the case where an adaptation already exists and has been maintained through intergenerational transmission, for example, among Indigenous populations [9, 14]. *Adaptation failure* in our model is represented by the loss of the adaptive behavior from the population, i.e., all agents adopt the non-adaptive behavior. Note, then, that it is possible for model agents to revert to the non-adaptive behavior through social learning after learning the adaptive behavior (the exact model learning process is explained in the Model section below). When either adaptive success or failure occur we say that either the adaptive or non-adaptive trait has *fixated*, respectively. We will show that adaptation success is significantly more likely when minority groups start out knowing the adaptive behavior, indicating their role as adaptation *incubators*. We will show that adaptation success is also significantly more likely when the majority group has a relatively high degree of homophily in order to protect the adaptive behavior once it has diffused into the majority group, indicating the majority group’s role as an adaptation *reservoir*, preserving the adaptation from cultural extinction. Our work here focuses on adaptation in the context of climate change, but our model and results extend to the broader process of the diffusion of any beneficial, culturally-transmitted behavior in heterogeneous populations.

Our majority-minority group structure is homologous to theoretical core-periphery social structures, where the *core* group is typically larger with most of its connections being in-group connections, while the groups on the *periphery* have smaller populations and have relatively more connections to the core group than vice-versa [10]. Too often, socially peripheral groups are not included in planning or implementing climate change adaptation efforts, which impedes the diffusion of adaptive practices [7]. Empirical and theoretical work in cultural evolution has shown that homophilous, heterogeneous social structure, characterized by community structure of the networks on which innovations diffuse, promotes greater cumulative cultural complexity [15–17]. Diversity in social structure can support problem-solving [18, 19] and prescient ideas often emerge from the peripheries of metapopulations [20]. While homophilous subgroups can promote the development of adaptations and support minority groups, social cohesion can also stifle innovation and lead to conflict [8, 21].

We chose to construct our model in terms of *majority groups*, *minority groups*, and *homophily levels*, instead of *core* and *periphery*, or other potential names, because the meaning is transparent: the minority group is the one with fewer group members compared to the majority group, and group-specific homophily levels modulate how frequently group members learn from others from their own group compared to members of the other group. This choice allows us to understand the effect of semi-structured learning: in our model, teacher selection is not fully constrained by a social network that would assume no social learning occurs outside of one’s social connections. A *teacher* in our model is any agent from whom another agent learns either the adaptive or non-adaptive behavior. At the same time, our model population is not well-mixed, which would mean social learners choose a teacher independent of group membership. Our work, then, complements related studies that used alternative model formulations. For example, Lieberman, Hauert, and Nowak (2005) found that network structure strongly constrained

adaptive trait fixation and evolutionary game dynamics [22]. On the other hand, Deffner and Kandler (2019) found that idealized agents evolved strategies to balance fast innovation with more sustainable long-term adaptations in a well-mixed, fitness-biased learning model; in that model, simulated learners chose a fully-random subset of teachers from a large population, then learned from the best-performing teacher [23]. Our minority-majority approach takes a middle ground, representing the fact that human social networks constrain who we interact with, but we also regularly interact with strangers.

Our model most closely represents those climate change adaptations that may spread from one person or household to another. The case of climate change adaptation in South Pacific Island nations provides several useful examples to which our model may be applied, where the spread of adaptations has been observed to require dedicated inclusion of minority-group populations often spread out among several islands, physically and socially separated from urban, governmental centers located on separate islands [24–26]. Torres Strait Islanders in the South Pacific, for example, have historically dealt with non-anthropogenic climate change, and have culturally-evolved practices for tracking seasonal weather patterns and timing crop planting that have not widely diffused to all who might benefit from adopting them [14]. Adaptive practices like this for subsistence farming will soon be widely in demand due to anthropogenic climate change [27]. Such practices tend to diffuse predominantly through person-to-person or household-to-household learning [28, 29]. Mangrove ecosystem management is another strategy known by South Pacific Islanders for mitigating sea level rise that could spread person-to-person [5]. Mangrove ecosystem management is likely a more successful strategy for mitigating rising sea levels compared to seawall construction often promoted by international development agencies. Seawalls often fail because they do a better job keeping water inland once water has breached a wall, effectively acting as a maladaptive dam [30]. Some local and Indigenous South Pacific Islanders know of the benefits of mangrove management and the harms of seawalls, but many others do not. Such maladaptation often occurs when urban-based governments implement plans developed by rich-country development actors and ignore local, Indigenous knowledge [6, 9, 26]. In general, local, Indigenous residents of a place have historically dealt with non-anthropogenic climate change, and have a repertoire of strategies that could effectively deal with the problem, if only others would adopt them instead of exogenously-planned projects [9].

Person-to-person or household-to-household social learning dynamics have been observed in other climate change adaptation cases where adaptation success requires the widespread diffusion of an adaptive practice, such as the adoption of residential rooftop solar photovoltaic installations [31]. Larger-scale climate change adaptation projects that require institution- or government-level change, such as transitioning away from fossil-fuel-burning power generation, may require explicit modeling of those institutions and their constituents [32, 33]. Even at the institutional level, the model presented here may provide useful context for understanding knowledge transfer among constituents who help decide which actions their institutions will pursue.

2 Model

To understand how minority groups can incubate climate change adaptation and majority groups can preserve climate change adaptation, we developed an agent-based model to represent a community metapopulation as simulated individuals, *agents*, who perform behaviors with different fitness; agents interact to learn behaviors from other agents [34]. Model metapopulations are composed of two groups: one is the minority group that accounts for a fraction $m \leq 0.5$ of the total metapopulation, N , while the other group is the majority that accounts for a fraction $1 - m$ of the metapopulation.

Following a cultural evolutionary approach, adaptive and non-adaptive behaviors are each represented as a trait held by each agent. We assume one agent from the minority, one agent from the majority, or one agent from each group begins the simulation with the adaptation. Traits are transmitted between agents through payoff-biased social learning [35, 36] to give social learning the greatest possible chance of success, i.e., we continue to focus on the ideal case. Social learning is where homophily matters since homophily specifies to what extent learners prefer teachers from their own group. Group structure and social connectivity are specified via model parameters of homophily and group size. Our primary out-

come measure is the success rate, i.e., how frequently adaptation success occurred over 1000 simulation trials. We explain the model dynamics, parameters, and computational analyses in more detail below.

To harmonize our presentation with the standard *Overview, Design, and Details* protocol, we have already introduced the *purpose* (ODD “overview”) and *design concepts* (ODD “design”) of our model; the *variables* and *process overview* (also from the ODD “overview”), and *initialization, input, and submodels* (ODD “details”) are described in detail below [37].

2.1 Model dynamics

The model dynamics proceed in three consecutive stages: first, agents are initialized with a group identity, group-level homophily, and whether they practice the adaptation or not. Homophily is represented by the agent’s preference to learn from within their group. Specifically, homophily specifies how much more frequently they learn from their in-group (Equation 1) compared to their out-group (Equation 2). On each time step, agents select which group to learn from, then select a teacher from the chosen group. Next, the agents engage in one round of learning per time step until one behavior or the other fixates in the simulated metapopulation, meaning all agents have trait a , or all have A .

Initialization. We assume that at $t = 0$ there is an innovative trait a that is introduced into the population by one individual in either the minority group or the majority group, or one individual in each group, while the rest of the population has non-adaptive trait A . We assume the fitness of trait a is greater than the fitness of trait A , written $f(a) > f(A)$ where $f(T_i)$ represents the fitness of agent i ’s trait T_i . Minority and majority group members are initialized with static homophily values h_{\min} and h_{\max} , respectively. Homophily can take values continuously between 0 and 1, though we ignore $h_{\min} = h_{\max} = 1.0$ when the trait is only introduced in one of the two groups since fixation is impossible in this case. When $h_{\min} = h_{\max} = 1.0$ and both groups are initialized with a , then the probability of fixation is the product of the two individual fixation probabilities since the two groups do not learn from one another.

The minority group fraction, m , is set constant to be a fraction of the total population, N . In the main text we set $m = 0.05$ ($m = 0.2, 0.35, 0.5$ tested in the Supplement) and $N = 1000$ ($N = 50, 100, 200$ tested in the Supplement). This means that in our simulations analyzed in the main text, the minority group size was 50 and the majority group size was 950.

[TABLE 1 ABOUT HERE]

Asymmetric-homophilous learning. At each model time step, each agent selects and learns from another agent, its teacher, weighted by prospective teachers’ group membership and relative fitness within its group. The probability an agent learns from its own group is

$$\Pr(\text{Learner chooses in-group teacher}) = \frac{1 + h}{2}, \quad (1)$$

where h is the agent’s group’s homophily value. The probability of learning from an out-group member is

$$\Pr(\text{Learner chooses out-group teacher}) = \frac{1 - h}{2} \quad (2)$$

Therefore the probability a learner, i , selects a given teacher, j , from group G is

$$\Pr(i \text{ selects teacher } j \in G) = \frac{1 \pm h}{2} \frac{f(T_j)}{\sum_{k \neq i \in G} f(T_k)}, \quad (3)$$

where the first fraction in the product on the right hand side of Equation 3 is the probability of selecting either the in-group ($\frac{1+h}{2}$) or out-group ($\frac{1-h}{2}$), and T_k is the trait of agent k . There is no learning noise or miscommunication in this model, so learner i adopts its teacher’s trait T_j . Trait updating does not occur immediately. First, all agents perform teacher selection and learning, but the learned trait is only adopted after all agents have selected and learned from a teacher, i.e., after the round is complete.

[FIGURE 1 ABOUT HERE]

Stopping condition. The simulation ends with adaptation success or failure, i.e., all agents have trait a , or all have A .

Example model dynamics. To clarify the model, consider the following example learning dynamics for minority and majority group members, i_{\min} and i_{maj} , respectively, in Figure 1. Let the total metapopulation be composed of $N = 7$ individuals and let $m = \frac{3}{7}$, so three agents are in the minority group and four in the majority. Let the minority have a group-level homophily value of $h_{\min} = 0.2$, meaning minority agents have a 60% chance of selecting a member of their own group to learn from, and a 40% chance of learning from a member of the majority group; let the majority group have a group-level homophily value of $h_{\text{maj}} = 0.6$, meaning a majority-group agent has a 80% chance of selecting a teacher from its own majority group, and a 20% chance of selecting a minority-group teacher (Figure 1A). Let one agent of three in the minority have the adaptive behavioral trait a , while two members of the four-member majority group have adaptive behavioral trait. Assume the non-adaptive fitness is $f(A) = 1.0$ and the adaptive fitness is $f(a) = 1.2$. Once each agent selects its group, then learning is fitness-biased within the chosen group (Figure 1B). If i_{\min} chooses to learn from either its own minority group or the majority group then it has a 0.55 chance of learning adaptive behavior a , since self-learning is not allowed in the model and thus half of the prospective teachers from each group have the adaptive trait, a . If i_{maj} chooses to learn from the minority there is one agent of three that has the adaptive trait, which results in a probability of 0.375 of learning the adaptive behavior from the minority group; if i_{maj} chooses to learn from its own group, two of the other three agents in its group have the adaptive trait, and so there is a probability of 0.71 that the agent adopts the adaptive behavior. This process continues for all agents at each time step; the model continues to step until adaptation success or failure, i.e., all agents have trait a or A , respectively.

2.2 Computational analysis

Our primary outcome variable, the *success rate*, is the frequency of adaptation success across 1000 simulation trials for each parameter setting of interest. We also observed, and calculated the mean of, the number of steps to adaptation success or failure across trials. This will help us understand the time course of the spread of adaptive behaviors, which could be practically useful when evaluating whether or not to abandon an intervention to spread an adaptation.

2.3 Implementation

The model was implemented in the Julia programming language [38] using the Agents.jl package [39]. Plots were made using the ggplot2 library [40] in R [41]. Model and analysis code is publicly available on GitHub (<https://github.com/eehh-stanford/SustainableCBA>) and the software version used for our Analysis here has a persistent DOI hosted by Zenodo (<https://doi.org/10.5281/zenodo.7976114>). Simulation output data used for our Analysis here is available through the associated Open Science Foundation repository for this project (<https://osf.io/cd9hx/>).

3 Analysis

To demonstrate that homophily and group structure can promote adaptation success via minority adaptation incubators and majority adaptation reservoirs, we systematically varied minority and majority homophily levels in the model, h_{\min} and h_{maj} , respectively (Figure 3), and observed how frequently the adaptive behavior swept through the population (*success rate*), becoming adopted by each agent. We observed that initializing the adaptation in the minority group is critical to increased success rate (Figure 2). However, we also find that success rate is most sensitive to majority homophily whether the

adaptation is initialized in the minority group, the majority group, or both, which indicates it is important for the majority group to guard its adaptive reservoir in case the adaptation is lost among the minority group through drift (Figure 3). To confirm our interpretation that minority groups act as incubators and majority groups as reservoirs, we inspected individual simulation time series and observed some cases where majority adaptation adoption lagged behind minority adoption (minority incubator), and some cases where the majority population had accumulated a large proportion of adopters while the minority adopter prevalence fell or vanished (Figure 4). Finally, we analyzed the number of time steps to adaptation success or failure across our simulation trial conditions—adaptation success takes longer, while failures “fail fast,” which highlights the need for patience and resources once an adaptation begins to take hold in a minority-majority-structured population (Figure 6).

Minority-group adaptation-incubator effect. Minorities are critical to better chances of adaptation success, and in fact smaller minorities do better than larger minorities. First, note that when the adaptation was initialized in the majority group that overall success rate was significantly lower on average across all h_{\min} and h_{maj} settings (Figure 2), and in many settings the success rate is 0 (Figure 3). In our sensitivity analyses we set the minority fraction to $m = 0.2$ and observed maximum success rates of 0.6 (Figure S4; Figure S5, top row), whereas in our main analysis success rates maxed out around 0.7 (Figure 3). Maximum success rates were reduced further when $m = 0.35$ and when group sizes were set equal, $m = 0.5$ (Figure S4; Figure S5, middle and bottom rows).

Why should smaller minority group populations improve adaptation success rates, and why should certain values of homophily amplify this effect? First, consider the difference in minority sizes, ignoring the effect of homophily. Consider the initial case where one agent in the minority has the adaptive trait. Smaller minority sizes result in a higher probability of selecting the agent with the adaptive trait at random when an agent must first select which group to learn from, as we have implemented here. In our model, with $N = 1000$ and $m = 0.05$ there is a $\frac{1}{2} \cdot \frac{1}{50} = \frac{1}{100}$ probability that the agent with adaptation is selected at random. When $m = 0.2$ this probability decreases to $\frac{1}{2} \cdot \frac{1}{200} = \frac{1}{400}$. Homophily contributes to this *incubator effect* by leading members of the minority to focus more on what their in-group is doing, and their in-group is the one with the beneficial adaptation. As long as homophily is not too great, the adaptation will diffuse into the majority group as well. When $f(a) = 1.05 \approx f(A)$, adaptations mostly fail to diffuse through the metapopulation at all when they start in the majority group only; when $f(a) = 2.0$, adaptations initialized in the minority group always succeed across a wide range of h_{\min} and h_{maj} , but often fail when initialized in the majority (Figure S7; Figure S8).

[FIGURE 2 ABOUT HERE]

Majority-group adaptation-reservoir effect. While minority group participation is essential to incubate an adaptation, we found majority group homophily had the largest effect overall on adaptation success. For any value of h_{maj} , increased h_{\min} does not change the success rate much, but when h_{maj} is set to its optimal value for a given h_{\min} , the success rate roughly doubled (Figure 3). This indicates that majority groups have an important role to play as well, namely that of an adaptation reservoir. Once enough majority members learn the adaptive behavior, the majority group has a greater cultural inertia that will help maintain the adaptation with less adoption variance compared to the minority group, and so can rescue the adaptation from extinction when the adaptation vanishes from the minority group.

[FIGURE 3 ABOUT HERE]

Time series of adaptation diffusion support this interpretation. If minority groups do indeed act as incubators, and majority groups as adaptation reservoirs, then this should be reflected in the time series of adaptation prevalence in the two groups. Indeed, time series of adaptation prevalence among the two groups further supports the interpretation that the groups have complimentary incubator-reservoir roles (Figure 4). For approximately optimal homophily levels $h_{\min} = h_{\text{maj}} = 0.75$, identified by reading off the heat maps in Figure 3, we see some cases where adaptation success was preceded by minority incubation

when the minority starts with the innovation (Figure 4A). However, even when the minority group starts with the innovation, some adaptation successes depended on the majority group protecting the adaptation while the adaptation vanished from the minority group. Similarly, when the majority started with the adaptation, we see cases where the majority again protects the relatively rare adaptation before adaptation success (Figure 4B). However, in this same setting there is one trial where the adaptation diffused into the minority group after starting in the majority group, and the minority group incubated the adaptation for a period.

[FIGURE 4 ABOUT HERE]

Successful adaptation takes time. To complete our analysis we calculated the mean time to achieve adaptation success or failure across each group-start condition broken out by success or failure. We also calculated the mean time to fixation across successful and failed adaptation efforts across all homophily settings. Success was achieved faster when the minority group or both groups started with the adaptation (Figure 5). The region of maximal time steps to fixation mostly mirrors the region of maximal success rate in the heatmaps in Figure 3. This indicates patience is required for successful adaptations. It also suggests that failure will be relatively quick. This makes sense, since many more agents will have to adopt the adaptive trait for adaptation success, while relatively few with the adaptive trait will need to adopt the non-adaptive trait at the beginning of the simulations. Homophily can also affect the time to fixation, with higher minority-group homophily resulting in longer times to fixation (Figure 6B,C), but no boost in the success rate. In the Supplement we examine how different parameter settings for the population size, N , minority group fraction, m , and adaptive behavior fitness, $f(a)$ affect the number of time steps to success or failure. Briefly, time to fixation is inversely correlated with N (Figure S3); time to fixation is relatively unchanged by changes to m (Figure S6); and time to fixation is inversely correlated with $f(a)$ (Figure S9).

[FIGURE 5 ABOUT HERE]

[FIGURE 6 ABOUT HERE]

4 Discussion

In this paper’s idealized simulations, relatively small minority groups served an essential role as adaptation incubators, while homophilous majority groups supported the diffusion of adaptations by acting as an adaptation reservoir, with more agents available to maintain the adaptation than the smaller minority population. Therefore, it is practically important to include minority groups in adaptation efforts, as well as the equitable, just, morally upstanding thing to do. Adaptation success took significantly longer than failure, so patience and persistence are required, even in the ideal case. Our approach to understanding minority-majority dynamics utilized mechanistic modeling of cultural evolution, which should continue to serve an important role to connect individual- and dyadic-level cognitive learning mechanisms with more complex, but possibly less concrete, models of climate change adaptation dynamics [42]. In general, mechanistic, agent-based modeling approaches such as ours help social scientists avoid sprawling verbal theories that may be mismatched to statistical models not suitable for causal inference [43–45]. Moreover, stochastic agent-based models enable the inspection of path dependence on social outcomes [46, 47], including non-equilibrium social dynamics that other approaches may not generate [48]. Still, alternative formal approaches to modeling the diffusion of adaptations in minority-majority metapopulations could provide complementary insights—for example, a population-genetics approach might explain that minority groups act as better incubators compared to majority groups because selection is weaker when the adaptation is more rare [49, Ch. 3].

We assumed that all adaptations are identically transmissible, but cognitive, cultural, and physical

constraints are known to be important for predicting the cultural spread of information [50, 51]. For example, just as our physical bodies constrain the sort of cultural information humans generate and transmit between individuals in the laboratory [52], some adaptive traits may be favored due to shared in-group cultural experiences, which could be helpful for amplifying climate change adaptation [53]. Complex or taboo adaptive behaviors may require multiple teaching exposures before an individual adopts them [54], but we assumed a single exposure was always sufficient—modifying this single-exposure assumption may result in lower success rates. Inter-group enmity and discrimination, which we ignored in this model, could further undermine adaptation success [55]. Minority and majority groups may also influence culture in different ways, with minority influence possibly exerting influence indirectly but persistently [56, 57], which may boost success rates by strengthening the minority-group adaptation-incubator effect. Furthermore, we assumed that there is just one pre-existing trait that determines adaptive fitness. In reality, fitness is based on a suite of cultural traits that are often correlated both in their expression and their transmission [58, 59]. Furthermore, different traits or behaviors are often composed to form new composite cultural variants through cumulative cultural evolution [60, 61]. Group structure is known to co-evolve with cumulative cultural traits [15, 62, 63], which could have complex, unpredictable effects on adaptation success rates. Finally, we assumed that both the minority group and majority group members received the same fitness boost by adopting the adaptive behavior. In reality, however, an adaptation is likely to provide different value to different stakeholders. For example, mangrove planting and management may help mitigate sea-level rise along the coast in South Pacific Island nations [5], but does not directly help subsistence farmers deal with changing weather patterns in the highlands of these nations.

The principle of “fail fast” is well-known to software developers who move quickly and break small things as they build big things. Fail fast has also been identified as an important strategy for organizations [64]. This suggests that international development actors, local governments, and citizens implementing climate change adaptations should plan for a few quick failures, with adjustments in between trials, before the adaptation gains the sort of critical momentum to spread through the population. Furthermore, since adaptation success takes significantly longer than failure, planners should also account for extended periods of financial and technical support as adaptations spread. Pisor and colleagues [9] suggest that social insurance like basic income could facilitate climate-change adaptation in Indigenous and other subsistence populations by cushioning the downside risk of fast failure of potential climate innovations. Our model did not include any mechanism for learning from past failures, though learning from past adaptation failures has been identified as an important step for successful community-based (and other) adaptation efforts [65].

Our results support the suggestions by [10] and [9] that subsistence, frequently Indigenous, populations on the margins of larger more market-integrated populations might be a source of climate adaptation. Moreover, our results support the hypothesis that successful innovations tend to emerge from the peripheries of networks [66], rather than in the cores of networks [67]. These observations suggest the potential functional importance of minority communities for innovation and adaptation. As such, it is essential that minority populations retain cultural autonomy [9]. Hegemonic cultural forces can easily homogenize diverse populations. Models by Bunce and McElreath [8] suggest potential means, through the construction of protected “homelands” and resulting asymmetric interactions, by which minority cultural norms can be retained, even when there is a strong tendency for homogenization. In this regard, our results on the efficacy of minority-group-initiated adaptations, the results of Bunce and McElreath [8] on retention of minority norms, and the results of Derex and Boyd [15] on community structure in transmission networks facilitating greater cumulative cultural evolution, seem to be converging on a robust pattern: in the ideal case, population heterogeneity in the form of group structure tends to promote the diffusion of adaptive behaviors and practices.

5 Author contributions

M.A.T. and J.H.J. conceived of the project. M.A.T., A.L.S., and J.H.J. designed the model and analyses. M.A.T. implemented the model and analyzed simulation results. All authors wrote, edited, and revised

the manuscript.

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Tables

Table 1: Summary of model variables, their meaning, and their numerical values used in our computational analyses.

Variable	Description	Values tested (bold=default)
N	Population size	50, 100, 200, 1000
m	Fraction of population in minority group	0.05 , 0.2, 0.35, 0.5
h_{\min}	Minority homophily, specifies in-/out-group learning probability for minority group via Equations 1 and 2	{0.0, 0.05, 0.1, ..., 0.95, 0.99}
h_{\max}	Majority homophily, specifies in-/out-group learning probability for majority group via Equations 1 and 2	{0.0, 0.05, 0.1, ..., 0.95, 0.99}
A	Non-adaptive, or status quo, behavioral trait	N/A
a	Climate change adaptation behavioral trait	N/A
$f(A)$	Fitness of non-adaptive behavioral trait A	1.0
$f(a)$	Fitness of adaptive behavioral trait a	1.05, 1.2 , 1.4, 2.0
T_i	Behavioral trait of agent i	a, A

Figures

A

$$\Pr(i_{\min} \text{ learns from minority in-group}) = \frac{1 + h_{\min}}{2} = 0.6$$

$$\Pr(i_{\min} \text{ learns from majority out-group}) = \frac{1 - h_{\min}}{2} = 0.4$$

$$\Pr(i_{\text{maj}} \text{ learns from majority in-group}) = \frac{1 + h_{\text{maj}}}{2} = 0.8$$

$$\Pr(i_{\text{maj}} \text{ learns from minority out-group}) = \frac{1 - h_{\text{maj}}}{2} = 0.2$$

B

$$\Pr(i_{\min} \text{ learns } a \mid i_{\min} \text{ learns from minority}) = \frac{f(a)}{\sum_{i_{\min} \neq k} f(T_k)} = \frac{1.2}{2.2} = 0.55$$

$$\Pr(i_{\min} \text{ learns } a \mid i_{\min} \text{ learns from majority}) = 2 \cdot \frac{f(a)}{\sum_k f(T_k)} = \frac{2 \cdot 1.2}{4.4} = 0.55$$

$$\Pr(i_{\text{maj}} \text{ learns } a \mid i_{\text{maj}} \text{ learns from minority}) = \frac{f(a)}{\sum_k f(T_k)} = \frac{1.2}{3.2} = 0.375$$

$$\Pr(i_{\text{maj}} \text{ learns } a \mid i_{\text{maj}} \text{ learns from majority}) = 2 \cdot \frac{f(a)}{\sum_{i_{\text{maj}} \neq k} f(T_k)} = \frac{2 \cdot 1.2}{3.4} = 0.71$$

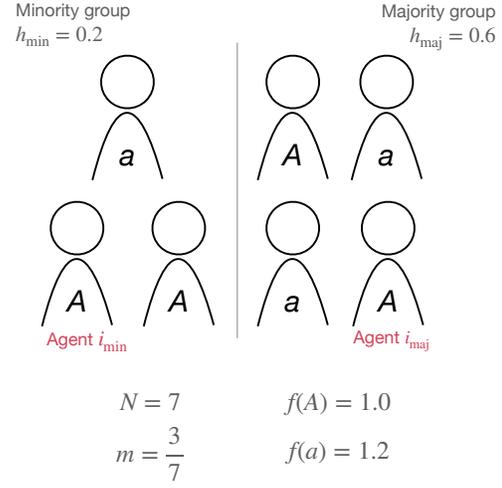
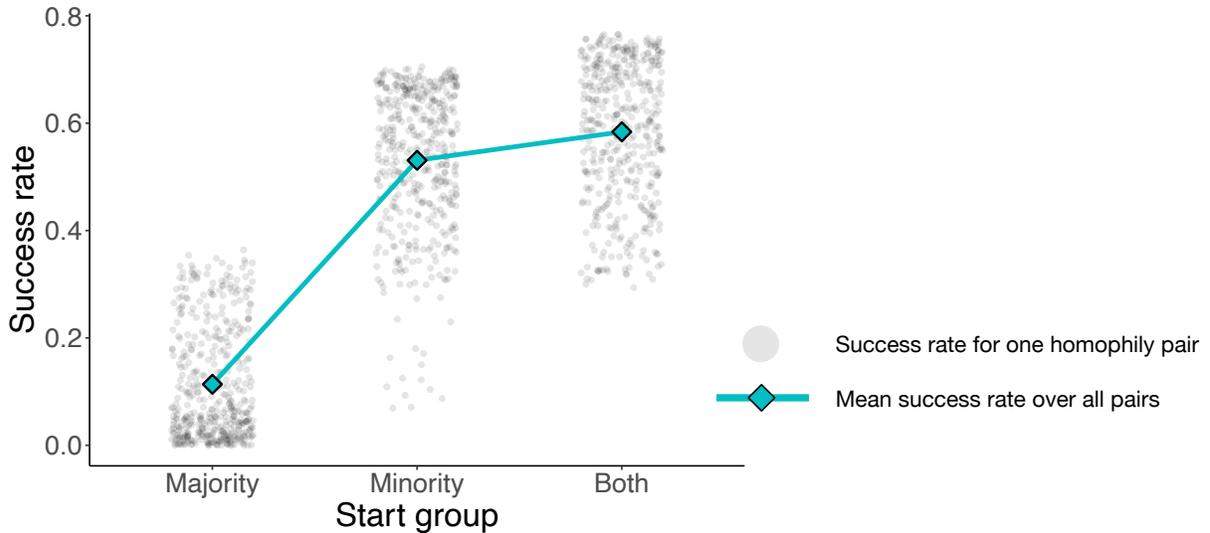
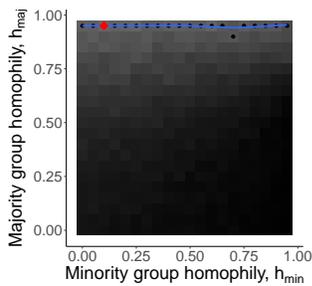


Figure 1: **Asymmetric-homophilous learning example.** We can break down teacher selection in our model into a two-step process, where first each agent selects which group to learn from, determined by group-level homophily (A). Then a teacher is selected at random, weighted by prospective teacher fitness (B). The probability any agent j is chosen as a teacher is given by the product of group selection probability and within-group relative fitness of a prospective teacher (Equation 3).

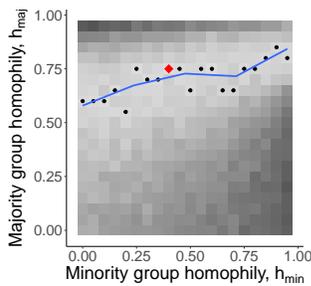
Figure 2: Success rate (y-axis) is greater on average when the minority group begins with the adaptation compared to the case where only the majority group begins with the adaptation (“Start group” on the x-axis). Each point represents the success rate from one minority-majority homophily pair, $(h_{\min}, h_{\text{maj}})$. Not all minority-start-condition success rates are greater than all majority-start-condition success rates. To understand the structure in success rate distributions, we must inspect success rate over specific homophily pairs (Figure 3). $N = 1000$, $m = 0.05$, and $f(a) = 1.2$.



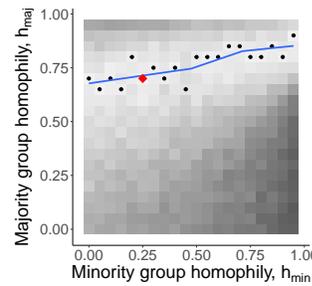
A, majority start



B, minority start



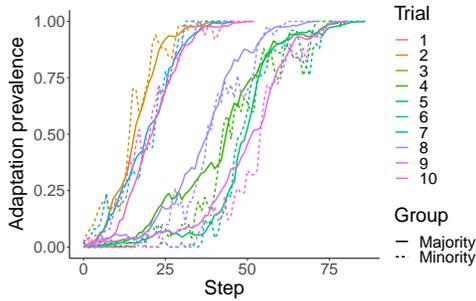
C, both start



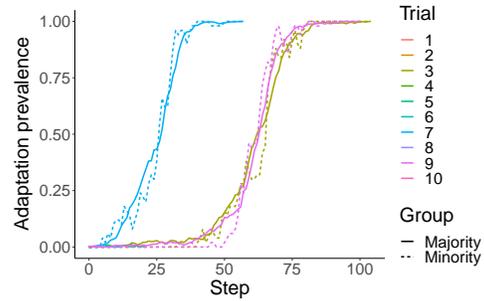
● Maximum success rate for given h_{\min} ◆ Maximum success rate across all h_{\min} and h_{maj} — LOESS-calculated trend line for visualization

Figure 3: When the minority group starts or both groups start with the innovation (B,C), success rates are greater overall compared to when the majority starts with the innovation (A), demonstrating the minority incubator effect. Success rates are greater still when both groups start off knowing the adaptive behavior (C). In all three cases majority group homophily has a greater effect on success rate than the minority group homophily level, i.e., the majority reservoir effect. $N = 1000$, $m = 0.05$, and $f(a) = 1.2$.

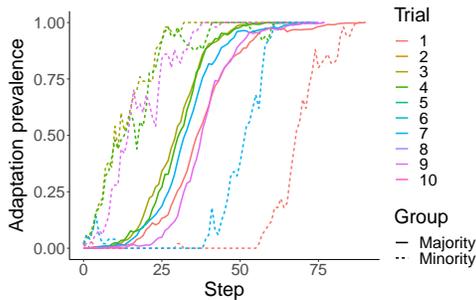
A, minority start, $h_{\min} = h_{\text{maj}} = 0.75$



B, majority start, $h_{\min} = h_{\text{maj}} = 0.75$



C, minority start, $h_{\min} = h_{\text{maj}} = 0.99$



D, majority start, $h_{\min} = h_{\text{maj}} = 0.99$

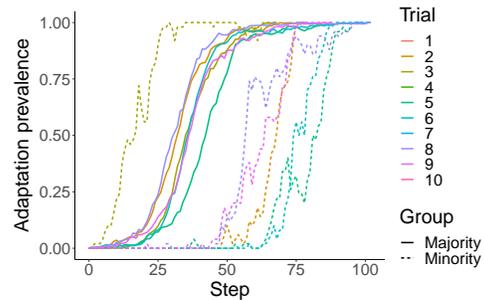
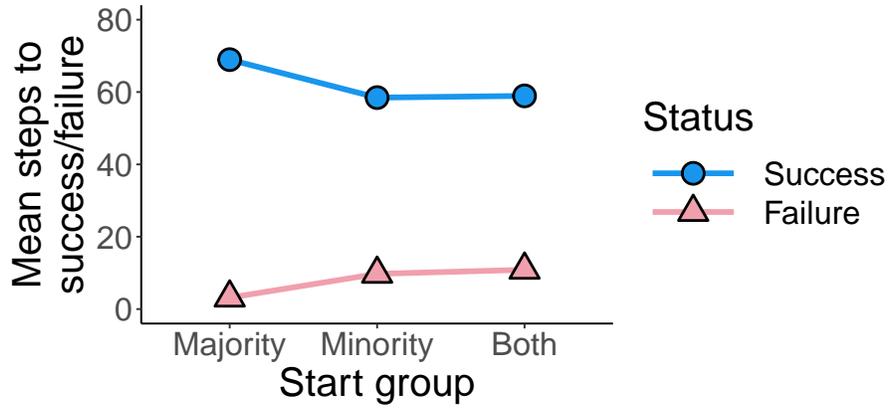
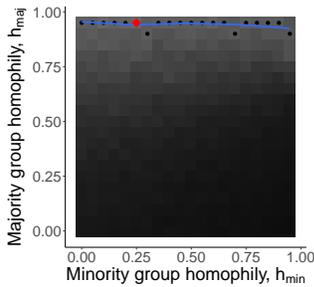


Figure 4: Time series of adaptation prevalence when the adaptation starts in either the minority (A,C) or in the majority (B,D) for two symmetric homophily values, $h_{\min} = h_{\text{maj}} = 0.75$ (A,B) and $h_{\min} = h_{\text{maj}} = 0.99$ (C,D). Ten trials shown for all four settings, though many quickly end with adaptation prevalence going to zero. The complementary roles of minority-group incubation and majority-group preservation are exaggerated for extremely high homophily: when the minority group starts with the adaptation, the minority group members often all learn the adaptation first, incubating the adaptation before it diffuses into the majority group (C). When the majority group starts, full adoption in the minority community lags full majority adoption (D), which also occurs for some trials as shown in (C). For one trial in (D), the adaptation diffused into the minority group, where the minority group then acted as an adaptation incubator.

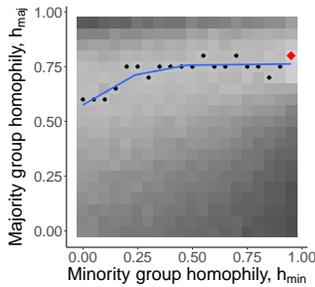
Figure 5: Successful adaptation efforts take significantly longer to achieve on average than failed efforts (mean steps to success or failure on y-axis; group start condition on x-axis). Success happens faster on average when the minority group starts with the adaptation. $N = 1000$, $m = 0.05$, and $f(a) = 1.2$.



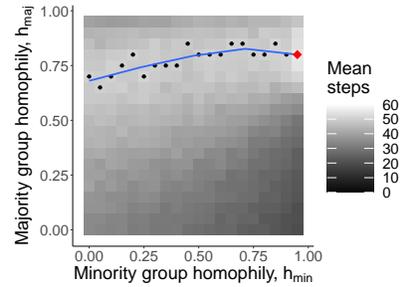
A, majority start



B, minority start



C, both start



● Maximum steps to fixation for given h_{\min} ◆ Maximum steps to fixation across all h_{\min} and h_{maj} — LOESS-calculated trend line for visualization

Figure 6: Mean number of steps to fixation across the same group start and asymmetric homophily values tested above. When success rates are greater, the time to fixation increases, indicating that patience is necessary for the spread of adaptations.

Minority-group incubators and majority-group reservoirs support the diffusion of climate change adaptations (Supplementary Material)

S1 Sensitivity analyses

In this Supplement we present sensitivity analyses to examine if and how model outcomes change under different settings for population size, N , minority group fraction, m , and the fitness of the adaptive behavioral trait, $f(a)$. Overall, success rate and time to fixation outcomes follow the same patterns as in the main analyses, with some important, and expected, differences. Briefly, we show in this Supplement that smaller population sizes ($N = 50, 100, 200$), compared to the main analyses ($N = 1000$), result in lower success rates and faster fixation times, but minority groups still act as incubators and majority groups as reservoirs (Subsection S1.1). When the minority group fraction was increased ($m = 0.2, 0.35, 0.5$) the incubator-reservoir dynamics were less pronounced—when $m = 0.5$, these effects disappeared as we would expect since there is technically no minority or majority group since each group is the same size (Subsection S1.2). Finally, a smaller adaptive fitness value ($f(a) = 1.05$ tested here) led to lower success rates and significantly longer steps to adaptation success when it occurred. Larger adaptive fitness values ($f(a) = 1.4, 2.0$) led to higher success rates and faster adaptation success when it occurred (Subsection S1.3). These analyses are reviewed in more detail below.

S1.1 Population size

We varied the population size, $N \in \{50, 100, 200\}$ (recall $N = 1000$ in the main text) to understand how this parameter affects overall success rates and time to fixation, and its effect on the incubator-reservoir dynamics observed in the main Analysis. Other parameters were set to their default values ($m = 0.05$, $f(a) = 1.2$). Overall, smaller population sizes did not significantly affect either the overall success rates (Figure S1) or incubator-reservoir dynamics (Figure S2). Adaptation success was faster overall when N was smaller (Figure S3).

Figure S1: Sensitivity analysis for mean success rate over groups for different N .

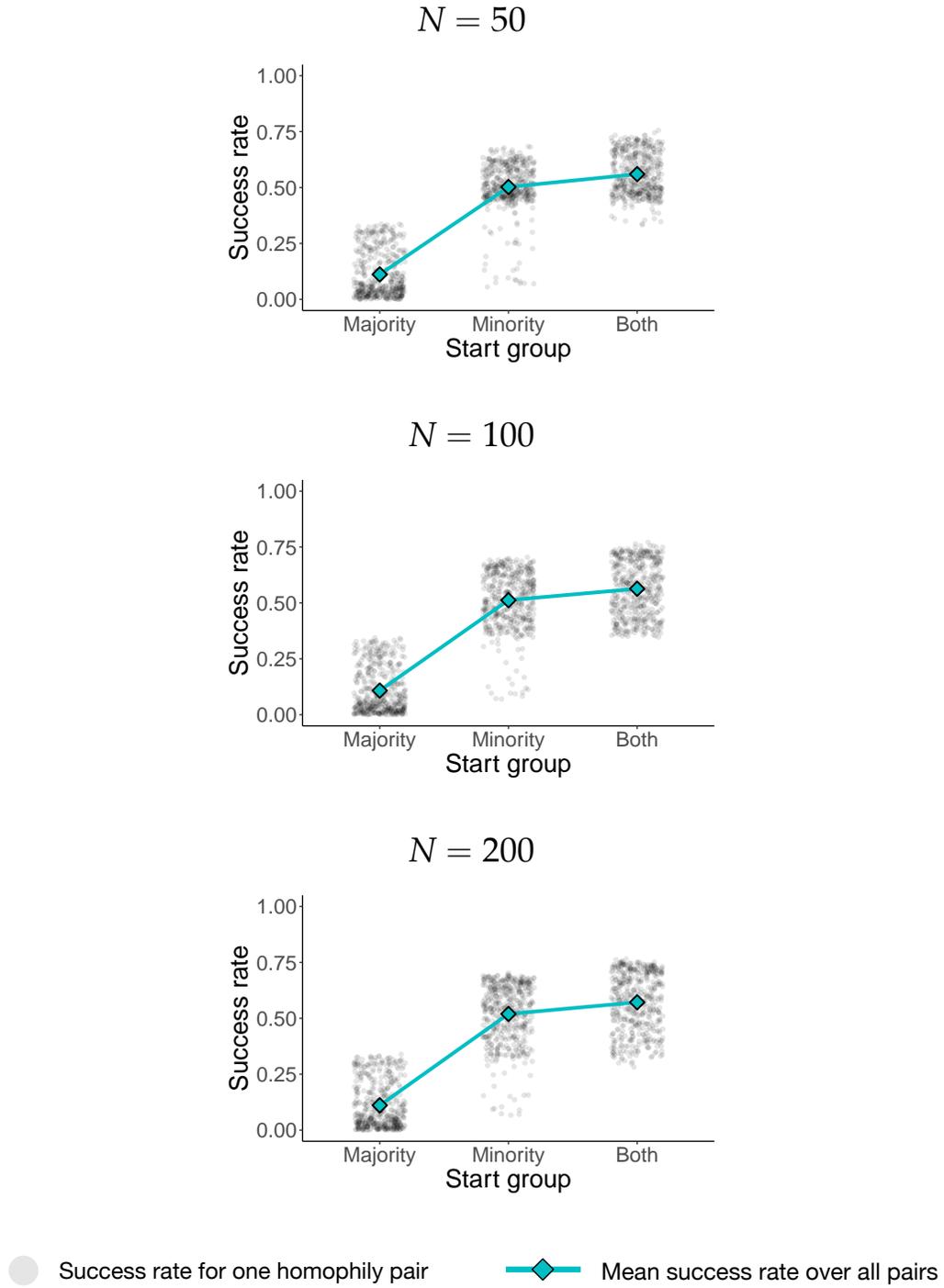
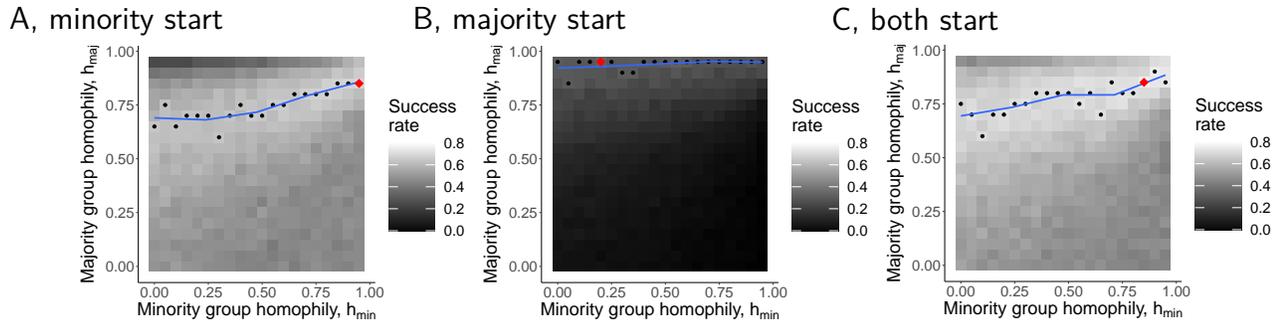
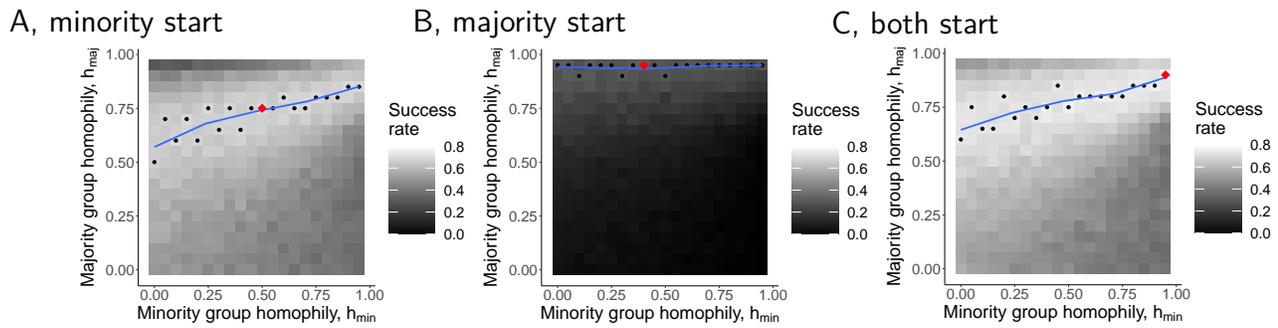


Figure S2: Sensitivity analysis for asymmetric homophily heatmaps of success rate for different N .

$N = 50$



$N = 100$



$N = 200$

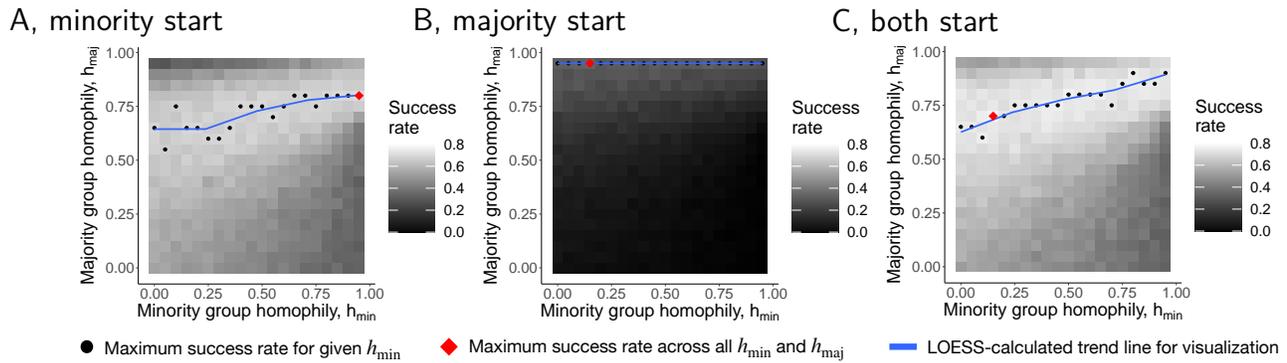
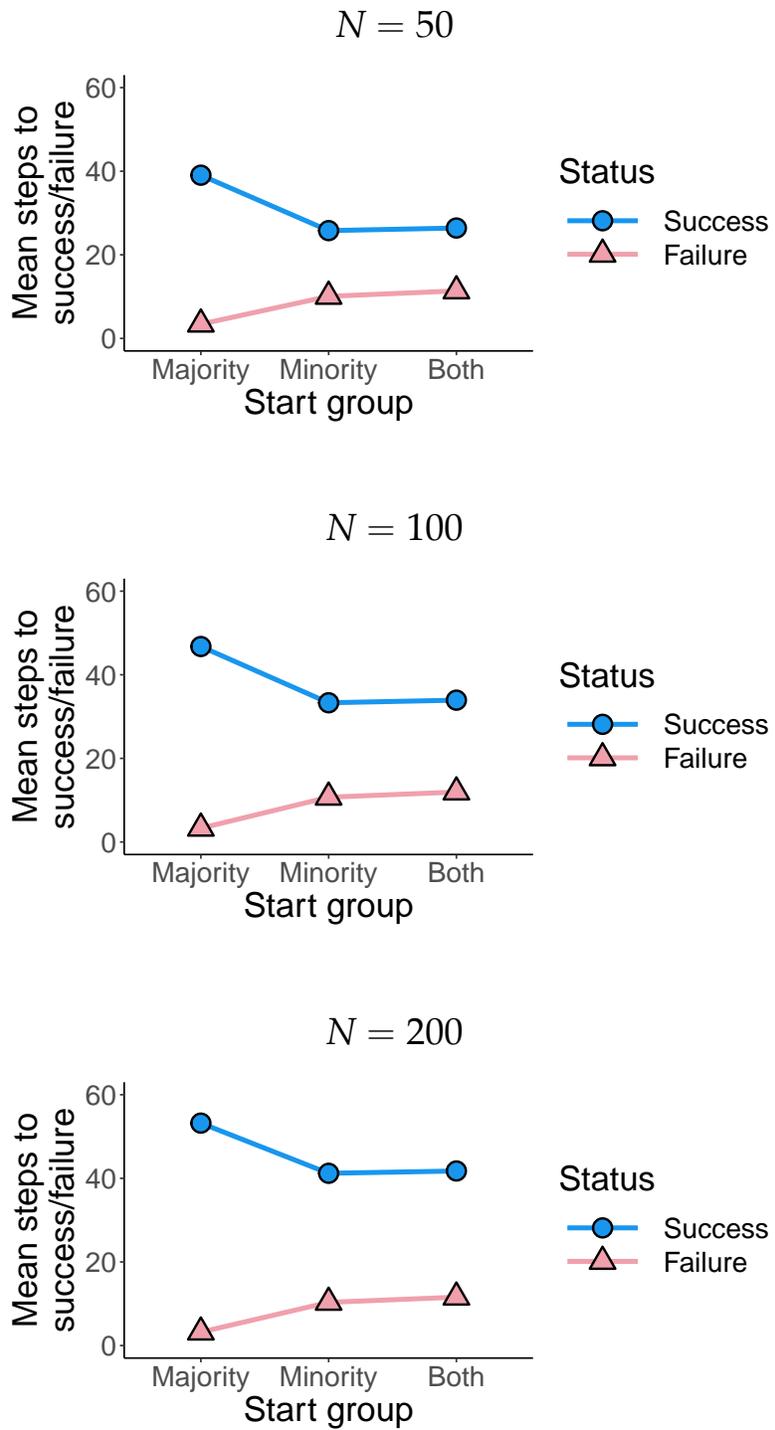


Figure S3: Sensitivity analysis for mean steps to fixation over groups over different N .



S1.2 Minority group size, m

Now we vary the minority group size, $m \in \{0.2, 0.35, 0.5\}$ (recall $m = 0.05$ in the main text), and set the other parameters to their default values ($N = 1000$, $f(a) = 1.2$). We measure success rate across group start and asymmetric homophily conditions, and mean steps to fixation across different group start conditions. Overall, success rates were lower when minority group size was larger and the adaptation started in the minority group or both groups (Figure S4) because in these cases drift was more likely to cause the adaptive trait to vanish from the minority group, i.e., the minority-group incubator effect was weaker (Figure S5). Mean steps to adaptation success or failure were relatively unchanged over the different values of m we tested (Figure S6).

Figure S4: Sensitivity analysis for mean success rate over groups for different m .

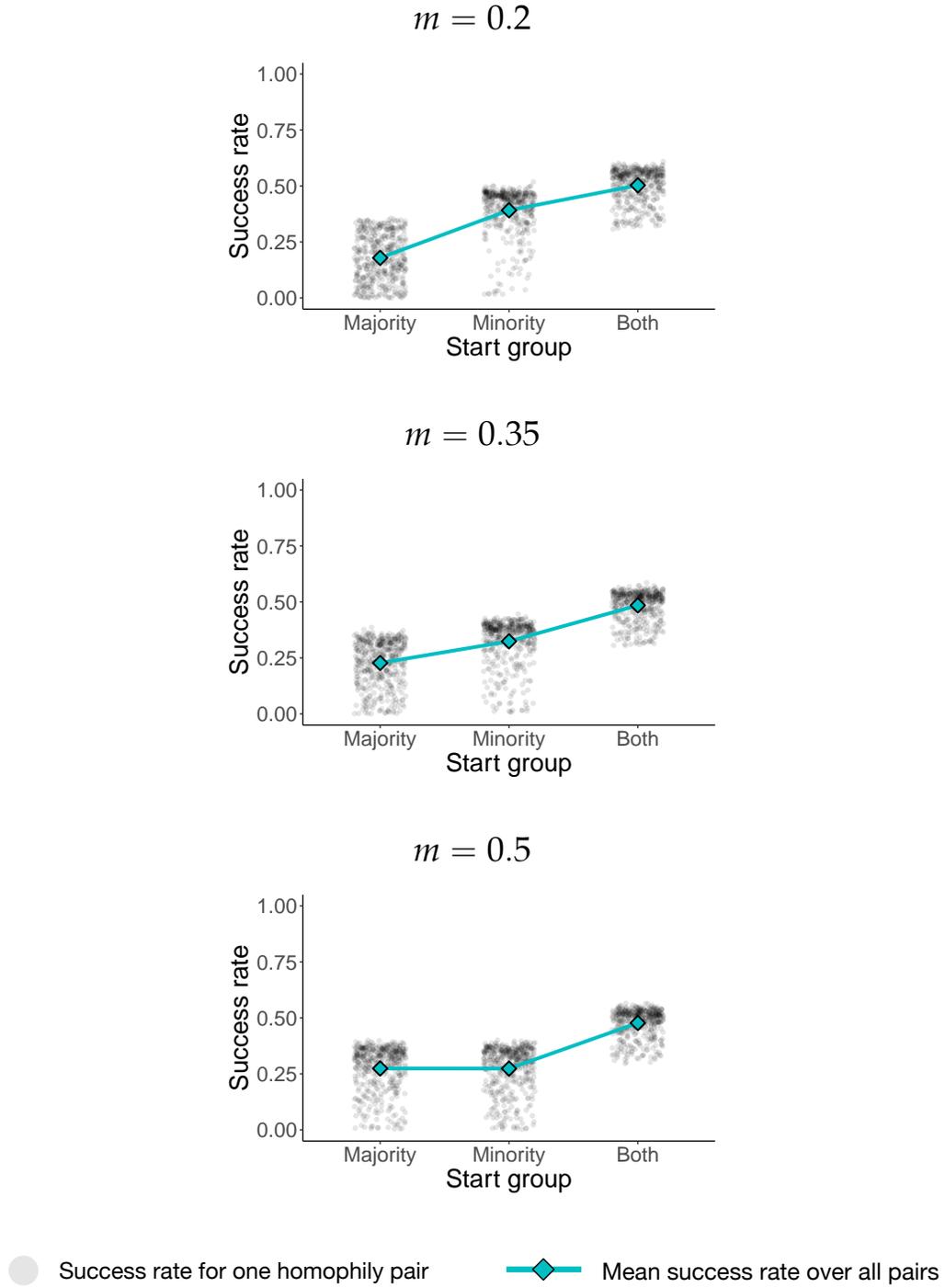
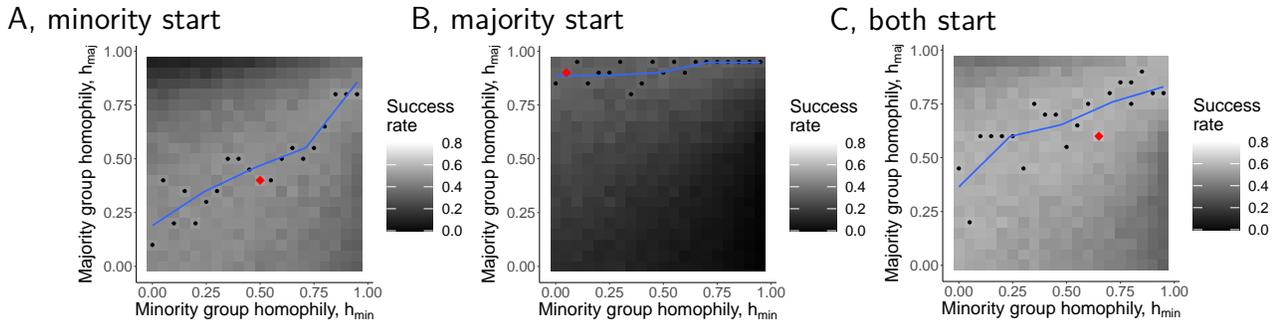
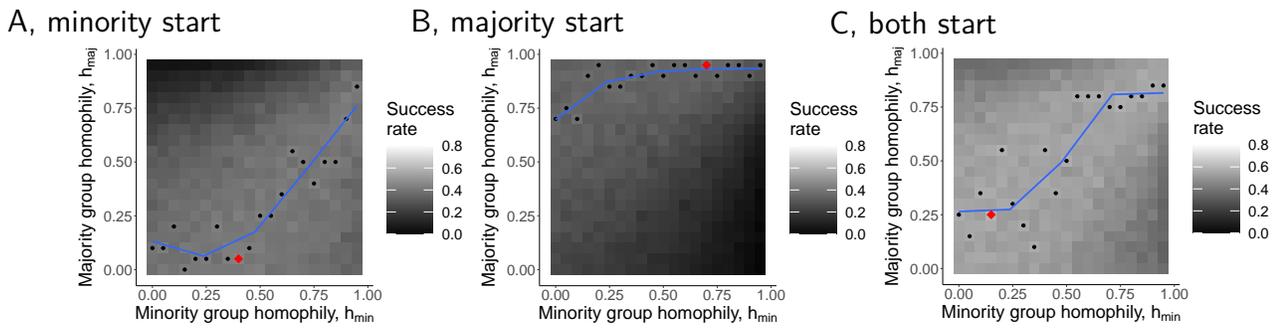


Figure S5: Sensitivity analysis for asymmetric homophily heatmaps of success rate for different m .

$m = 0.2$



$m = 0.35$



$m = 0.5$

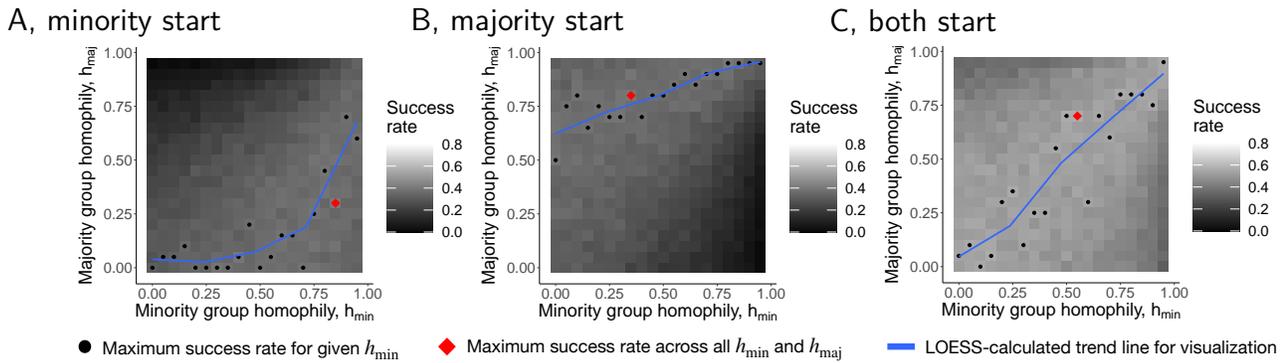
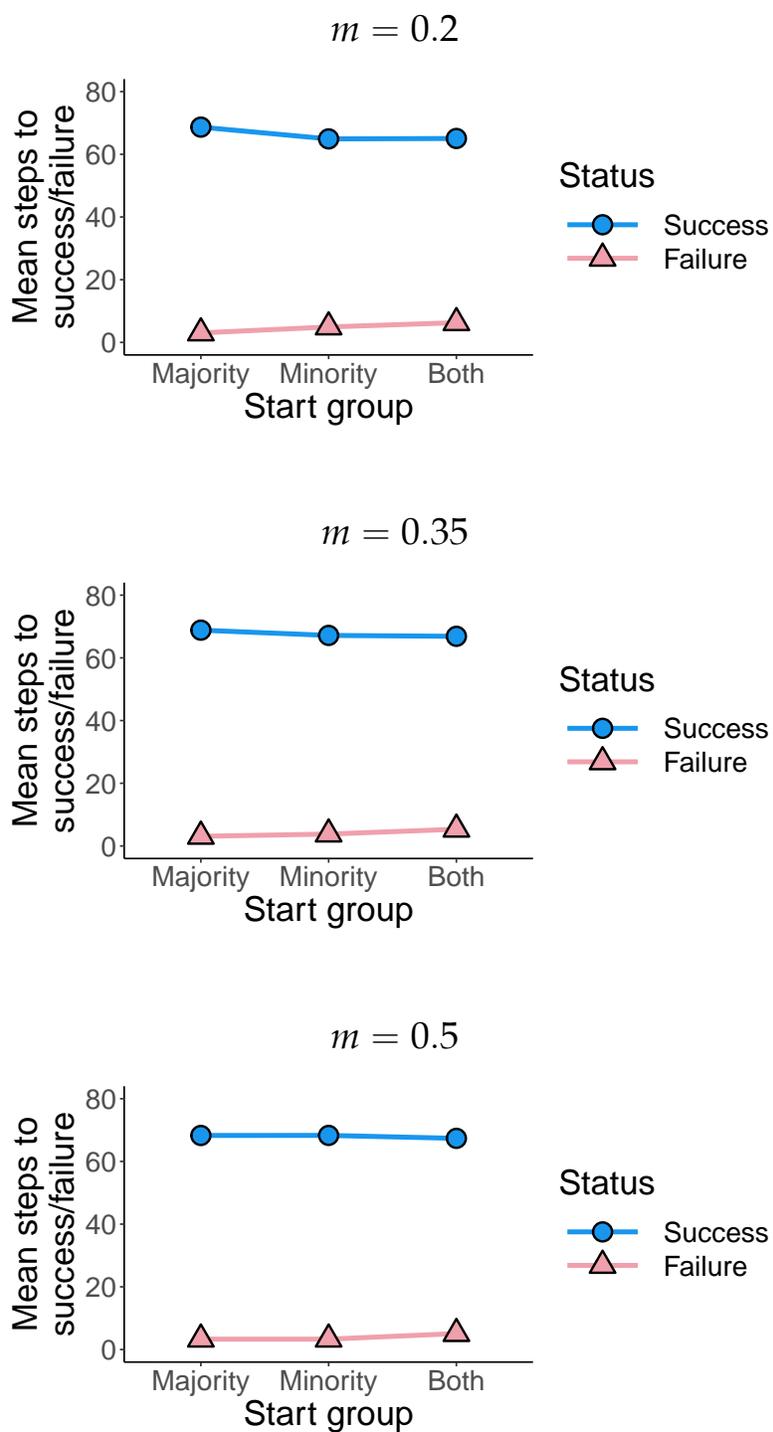


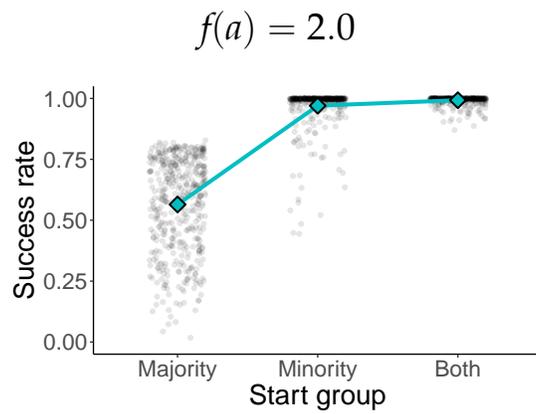
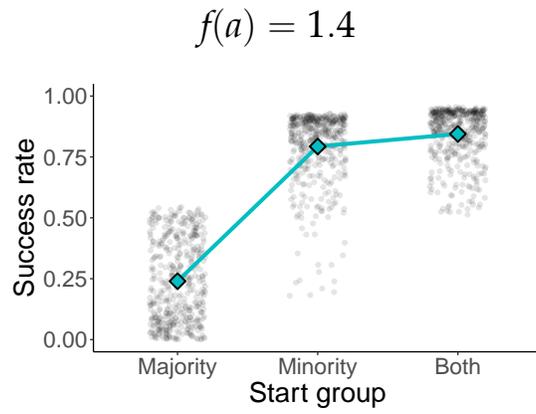
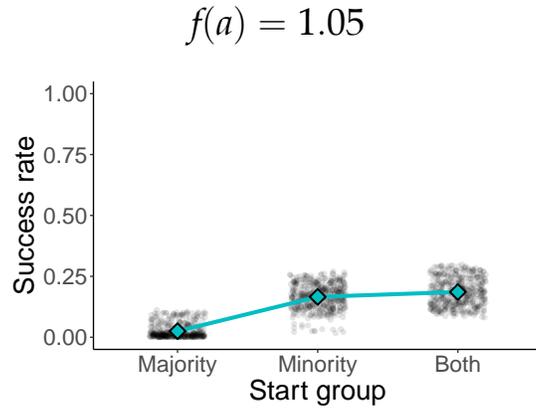
Figure S6: Sensitivity analysis for mean steps to fixation over groups over different m .



S1.3 Adaptation fitness, $f(a)$

Now we vary the minority group size, $f(a) \in \{1.05, 1.4, 2.0\}$ (recall $f(a) = 1.2$ in the main text), and set the other parameters to their default values ($N = 1000$, $m = 0.05$). For this comparison, we set the heatmaps' colormap to run from a success rate of 0.0 to 1.0. Note that when $f(a) = 2.0$ (bottom row of Figure S8) and the minority group or both groups start with the adaptation, many homophily settings result in guaranteed success, with success rates at a maximum of 1.0. Therefore there is no unique maximum success rate for these cases and the corresponding heatmaps are annotated with many red diamonds everywhere the success rate was 1.0. Overall, success rates were positively correlated with adaptation fitness, as expected since selection will be stronger as adaptation fitness increases (Figure S7; Figure S8). Similarly, mean steps to adaptation success or failure were inversely correlated with adaptation fitness since stronger selection means faster fixation for adaptation success (Figure S9).

Figure S7: Sensitivity analysis for mean success rate over groups for different $f(a)$.

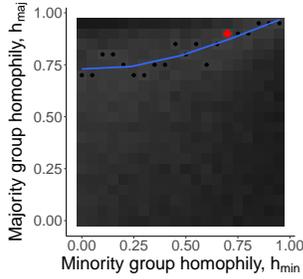


● Success rate for one homophily pair ◆ Mean success rate over all pairs

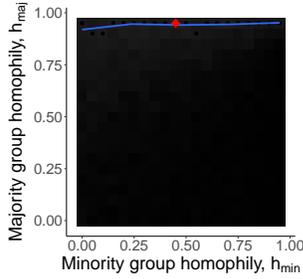
Figure S8: Sensitivity analysis for asymmetric homophily heatmaps of success rate for different $f(a)$.

$$f(a) = 1.05$$

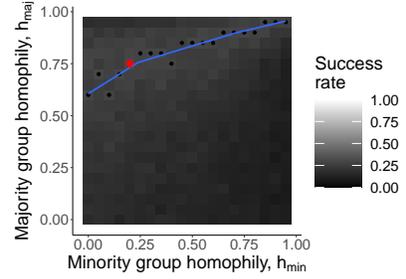
A, minority start



B, majority start

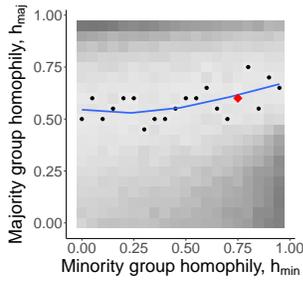


C, both start

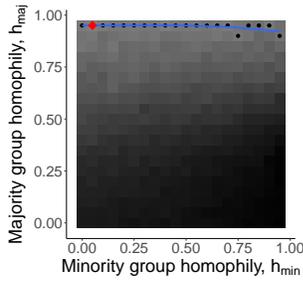


$$f(a) = 1.4$$

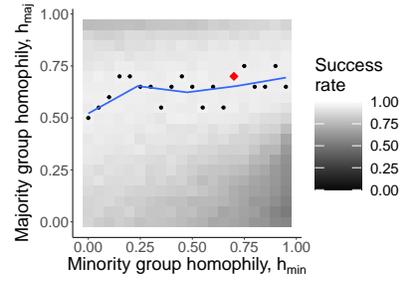
A, minority start



B, majority start

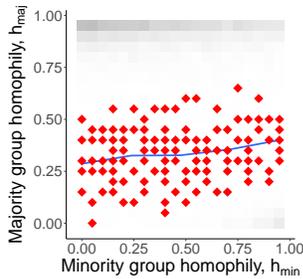


C, both start

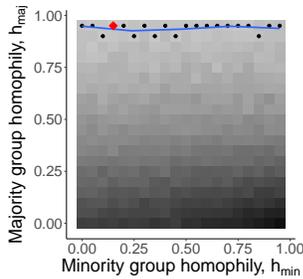


$$f(a) = 2.0$$

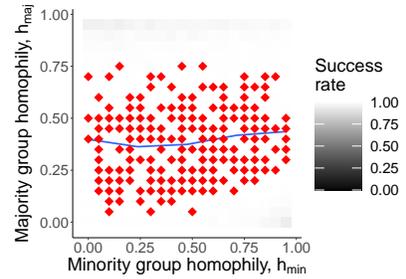
A, minority start



B, majority start



C, both start



● Maximum success rate for given h_{\min} ◆ Maximum success rate across all h_{\min} and h_{\max} — LOESS-calculated trend line for visualization

Figure S9: Sensitivity analysis mean steps to fixation over groups over different $f(a)$.

