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Authors

Turner, Matthew Adam
Signleton, Alyson L.
Harris, Mallory J.
et al.

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Minority-group incubators and majority-group reservoirs for promoting the diffusion of climate change and public health adaptations

Matthew A. Turner (maturner@stanford.edu), **Alyson L. Singleton** (asinglet@stanford.edu),
Mallory J. Harris (mharris9@stanford.edu), **Cesar Augusto Lopez** (cesarlop@stanford.edu),
Ian Harryman (ianharry@stanford.edu), **Ronan Forde Arthur** (rarthur@stanford.edu),
Caroline Muraida (caroline.muraida@stanford.edu), and **James Holland Jones** (jhj1@stanford.edu)

Stanford Doerr School of Sustainability, Social Sciences Division, Stanford University, Stanford, CA 94305 USA

Abstract

Current theory suggests that heterogeneous metapopulation structures can help foster the diffusion of innovations to solve pressing issues including climate change adaptation and promoting public health. In this paper, we develop an agent-based model of the spread of adaptations in simulated populations with minority-majority metapopulation structure, where subpopulations have different preferences for social interactions (i.e., homophily) and, consequently, learn deferentially from their own 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 novel adaptations, while majority groups act as reservoirs for the adaptation once it has spread widely. This suggests that population structure with in-group preference could promote the maintenance of novel adaptations.

Keywords: Anthropology, sociology, agent-based modeling, cultural evolution, group behavior

Introduction

Climate change threatens societies worldwide (Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022), but often most severely affects populations least responsible for greenhouse gas emissions (Althor, Watson, & Fuller, 2016). Similarly, global health problems disproportionately burden developing nations (Olusanya, Ubogu, Njokanma, & Olusanya, 2021), exacerbated by the climate crisis (World Health Organization, 2020). Help from rich countries is unreliable (Nunn & Kumar, 2019), so it is critical to understand which basic social factors affect the spread of climate change adaptations to better predict when and why different adaptation interventions succeed in order to maximize available adaptive capital. In this paper we analyze an idealized agent-based model of the spread of adaptations of the sort that might help those in developing nations adapt to climate change or promote public health. Cognitive science has an important role to play to help explain which real-world factors cause deviations from this ideal to occur.

Adaptation has several meanings within climate science, but here we adopt a general definition suitable for studying the spread of culturally-learned behaviors (Steward, 1955; Boyd, Richerson, & Henrich, 2011; Jones, Ready, & Pisor, 2021), including climate change adaptation or mitigation strategies and public health interventions. We define an *adaption* as a solution to a problem in the form of a behavior or practice that confers a greater fitness to those who employ the adaptation compared to those who do not (Jones et al., 2021). Our model and analyses thus apply broadly to the diffusion of any beneficial culturally-transmitted behavior in homophilous, heterogeneous metapopulations. *Adaptation success* in this model is when an adaptation spreads to every simulated individual (*agent*) in the population. *Adaptation failure* is when the adaptation disappears from the population. We will see that minority groups act as *incubators* in this setting because adaptation success is much more likely when minority groups start with an adaptation, and majority groups act in a complementary way, as *reservoirs*, to maintain large numbers of agents with adaptation know-how.

There is suggestive evidence indicating that climate change adaptations are more effective when they come from the within communities implementing them (Netting, 1993; McNamara et al., 2020). Several participatory, grassroots, or "bottom-up" strategies have been developed to foster the diffusion of adaptive behaviors, ecosystem protection, and regeneration, both for climate change and more generally, drawing on diverse social science sub-disciplines, including anthropology, sociology, and economics. The *community-based adaptation* approach aims to identify and promote socially-sustainable adaptations to climate change for vulnerable populations, where the focus is on how social interactions affect socio-ecological outcomes (McNamara et al., 2020). The *ecological-based adaptation* approach is similar but harnesses autochthonous positive feedback loops to boost ecosystem restoration and resilience to mitigate climate change impacts (Munang et al., 2013). Community-based adaptations and ecological-based adaptations have been most successful when they are led by local governments and when development actors account for ethnic, economic, and other demographic variables through repeated public meetings and other engagement events to foster buy-in from disparate groups; these interventions often fail when these fault

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lines are allowed to expand unabated (Nalau et al., 2018; McNamara et al., 2020; Casey, 2018). Similarly, public health interventions, for example against female genital cutting, are most successful when they account for the true heterogeneity of the population (Vogt, Mohmmed Zaid, Ahmed, Fehr, & Efferson, 2016; Efferson, Vogt, & Fehr, 2020; Ehret, Constantino, Weber, Efferson, & Vogt, 2022).

More homogenous, cohesive communities are often more resistant to deviance, beneficial or not (Coleman, 1988). This suggests that heterogeneity in population structure can actually facilitate the spread of innovations and the development of cumulative culture (Derex & Boyd, 2016; Centola, 2018). We operationalize social cohesion by group-level *homophily*, which specifies the tendency of group members to learn from within their own group versus from the out-group. In terms of social networks that arise from the aggregate of individual social interactions, greater homophily means stronger in-group social ties and weaker out-group social ties.

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 (Derex & Boyd, 2016; Derex, Perreault, & Boyd, 2018; Montrey & Shultz, 2022b). Transient diversity, suggesting heterogeneity in knowledge networks, can support problem solving (Zollman, 2010; Smaldino, Moser, Velilla, & Werling, 2022) and prescient ideas often emerge from the peripheries of metapopulations (Vicinanza, Goldberg, & Srivastava, 2022). Useful climate change adaptations may even already exisxt in socially-peripheral indigenous communities, such as Torres Strait Islanders in the South Pacific who have historically dealt with non-anthropogenic climate change, but whose methods for tracking seasonal weather patterns and timing crop planting have not widely diffused to all who might benefit from adopting them (McNamara & Westoby, 2016). Intriguingly, studies of the evolution of anti-microbial (and other drug) resistance (an acultural system) suggest that resistance often first takes hold in peripheral groups in metapopulations (Ariey, Duchemin, & Robert, 2003; Shapiro et al., 2020).

While homophilous subgropus can promote adaptation development and support minority groups, social cohesion can also stifle innovation and lead to conflict (Bunce & McElreath, 2018). For example, group membership has been observed to be more important to individuals than competence or reliability when choosing teachers (Cikara, Van Bavel, Ingbretsen, & Lau, 2017; Montrey & Shultz, 2022a). In the context of health behaviors, HIV pre-exposure prophylaxis (PrEP) adherence has been inconsistent in some trials due to negative stigmas associated with PrEP, likely leading to greater practice secrecy and reduced social exposure to others taking PrEP (van der Straten et al., 2014). Because of evidence for and against the benefits of minority-majority metapopulation structures, it is necessary to understand, in a simulated ideal case, whether minority-majority structure can promote adaptation diffusion, or whether such group structures impede adaptation diffusion.

To understand whether minority-majority metapopulation structure can promote the diffusion of adaptations, we developed an agent-based model of adaptation diffusion. Agent-based models are *mechanistic* models that specify (simplified) individual-level cognition and rules for interpersonal interaction, from which patterns in relevant outcome variables emerge—in this study, the primary emergent outcome is whether the adaptive behavior successfully diffused to all members of a simulated population, i.e., *adaptation success*. Mechanistic models of social behavior are useful for developing theories of social diffusion generally because mechanistic models require specification of essential components and their interactions. Specificity helps social scientists avoid sprawling verbal theories that may be mismatched to statistical models not suitable for causal inference (Kauffman, 1970; Yarkoni, 2022; Turner & Smaldino, 2022). Rigorous model development enables consistent experimental designs since experiments based on the same model are more likely to be commensurate; this would allow new climate change adaptation and public health intervention studies to multiply our understanding, instead of fracturing it across superficially disparate adaptation science sub-fields (Almaatouq et al., 2022).

Agent-based, cultural evolutionary models are well-suited for developing mechanistic *middle-range theories* (Merton, 1949; Hedström & Ylikoski, 2010) that typically straddle theoretical paradigms where constituent cognitive and social processes take place across different dimensional scales, i.e., different spatial, temporal, and population scales (Macy & Flache, 2009). Moreover, agent-based models promote the inspection of path dependence on social outcomes (Epstein, 1999; Turner & Smaldino, 2018), including non-equilibrium social dynamics that other approaches may not generate (Epstein & Hammond, 2002).

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 of simulated individuals, *agents*, who perform behaviors with different fitness; agents interact to learn behaviors from other agents (Fogarty & Kandler, 2020). 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 majority, one agent from the minority, or one agent from each group begins the simulation with the adaptation. Traits are transmitted between agents through payoff-biased social learning (Laland, 2004; Kendal et al., 2018) to give social learning the greatest possible chance of success. Social learning is where homophily matters since homophily specifies how frequently learners choose teachers from their own group. Group structure and social connectivity is specified via model parameters of homophily and group size. Our primary outcome measure is the *success rate*, i.e., how frequently the adaptation success occurred over 1000 simulation trials. We explain the model dynamics, parameters, and computational analyses in more detail below.

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 specifies how much more frequently agents 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 adopted the adaptive trait or all have adopted the non-adptive trait.

Initialization. We assume that at $t = 0$ there is an adaptive trait a that is introduced into the population by one individual in the *majority* group, the *minority* group, or one individual in *both* groups, 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_{maj}, respectively. Homophily can take values continuously between 0 and 1, though we ignore $h_{\text{min}} = h_{\text{maj}} = 1.0$ when the trait is only introduced in one of the two groups since fixation is impossible in this case. When $h_{\text{min}} = h_{\text{maj}} = 1.0$ 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 this paper's analyses we set $N = 1000$ and $m = 0.05$, meaning that the minority group size was 50 and the majority group size was 950. We test several alternative settings in the Supplement (`https://osf.io/br6zf`): $N = 50, 100, 200$, $m = 0.2, 0.35, 0.5$, and $f(a) = 1.05, 1.4, 2.0$.

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

Variable	Description	Values tested
N	Population size	1000
m	Minority group fraction	0.05
h_{min}	Minority homophily	0,0.05,..,0.95
h_{maj}	Majority homophily	0,0.05,..,0.95
A	Non-adaptive behavioral trait	N/A
a	Adaptive behavioral trait	N/A
$f(A)$	Fitness of trait A	1.0
$f(a)$	Fitness of trait a	1.2

Asymmetric-homophilous learning. At each model time step, each agent learns from another agent. A teacher is selected at random, weighted by the relative fitness of each agent and homophily values, implemented as follows. First, the learner agent decides whether to learn from its own group or the out-group, chosen at random, weighted by homophily. 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

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

Once a learner agent i selects group G to learn from, it then selects teacher j randomly, biased by fitness. Formally,

$$\Pr(i \text{ chooses } j \in G) = \frac{f(T_j)}{\sum_{k \neq i \in G} f(T_k)}, \quad (3)$$

where 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.

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. 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 group have a group-level homophily value of $h_{\mathrm{min}} = 0.2$, 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 $h_{\mathrm{maj}} = 0.6$, meaning a majority agent has a 80% chance of selecting a teacher from its own majority group, and a 20% chance of selecting a minority-group teacher. Let one agent of three in the minority have the adaptive behavioral trait a, while two members of the four-member majority group have the 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. 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.

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.

Implementation

The model was implemented in the Julia programming language (Perkel, 2019) using the Agents.jl package (Datseris, Vahdati, & DuBois, 2022). Plots were made using the `ggplot2` library (Wickham, 2016) in R (R Core Team, 2022). Model and analysis code is publicly available on GitHub (`https://github.com/eehh-stanford/SustainableCBA`).

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 2), and observed (1) how frequently adaptation success was achieved (the *success rate*); (2) time series of simulation trials to support our minority-incubtator and majority-reservoir interpretation; and (3) the mean number of time steps until either adaptation success or failure.

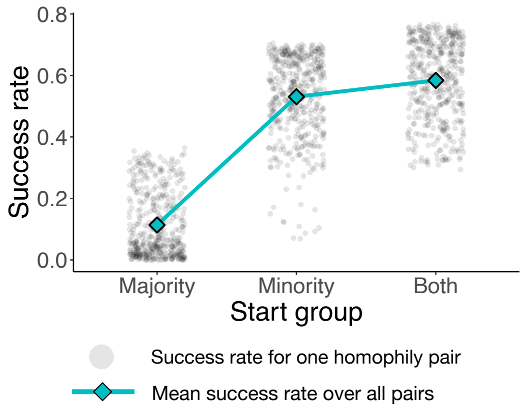
Minority-group adaptation-incubator effect. Minority groups are critical for adaptation success. Adaptation success rates were higher when the adaptation was initialized in the minority group or both groups compared to the majority-only start condition (Figure 1).

To understand this result, consider how different minority group sizes affect the probability of adopting the adaptive trait at model initialization, ignoring the effect of homophily by setting $h_{\mathrm{min}} = h_{\mathrm{maj}} = 0$ and ignoring payoff bias in teacher selection. Let one agent in the minority group have the adaptive trait. 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 the first model time step. When $m = 0.2$ this probability decreases to $\frac{1}{2} \cdot \frac{1}{200} = \frac{1}{400}$. Homophily amplifies this *incubator effect* by constraining minority group members to focus on their in-group which has the adaptation initially.

Majority-group adaptation-reservoir effect. While minority group participation is essential to incubate a novel adaptation, we found majority group homophily had the largest effect overall on adaptation success. For any value of h_{maj}, increased h_{min} did not change the success rate much, but when h_{maj} was set to its optimal value for a given h_{min}, the success rate roughly doubled (Figure 2). 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.

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 complementary incubator-reservoir roles (Figure 3). For

Figure 1: Adaptation 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, $(h_{\mathrm{min}}, h_{\mathrm{maj}})$.



approximately optimal homophily levels $h_{\mathrm{min}} = h_{\mathrm{maj}} = 0.75$, identified by reading off the heat maps in Figure 2, we see some cases where adaptation success was preceded by minority incubation when the minority starts with the innovation (Figure 3A). 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. This effect is exaggerated for large homophily values, $h_{\mathrm{min}} = h_{\mathrm{maj}} = 0.99$ (Figure 3B).

Successful adaptation takes time. To complete our analysis we calculated the mean time to fixation for adaptation success or failure for each start group setting (Figure 4). Successful adaptations take longer than failures. When the majority group starts with the adaptation, success takes longer still. This indicates patience is required for successful adaptations. Since the average success rate across all conditions was at best 80% (Figure 1), this indicates development agencies and local governments should be prepared for several failed adaptation diffusion efforts, and be prepared to support successful adaptation efforts that take significantly longer to diffuse through the population.

Sensitivity analyses. Aside from minor details, our analyses were robust to different population sizes, N, minority group fractions, m, and adaptation fitness values, $f(a)$. We tested $N = 50, 100, 200$; $m = 0.2, 0.35, 0.5$; and $f(a) = 1.05, 1.4, 2.0$. These analyses are available via the Open Science Foundation repository for this project, `https://osf.io/br6zf`.

Discussion

In this paper's simulations, relatively small minority groups served an essential role as adaptation incubators, while homophilous majority groups supported adaptation diffusion by acting as adaptation reservoirs, with more agents available to maintain the adaptation than the smaller minority group population. 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 (Barnes et al., 2020) and epidemiology (Galea, Riddle, & Kaplan, 2010). Future work, especially among cognitive scientists, might focus on how real-world adaptation in minority-majority populations deviates from the ideal, for example through political or ethnic tensions, or by cultural mismatches between adaptations and the populations responsible for their diffusion and maintenance.

Figure 2: While majority group-start success rates are lower overall (A), the majority group acts as a reservoir especially well when majority homophily is relatively high and the minority group starts with the adaptation (B).

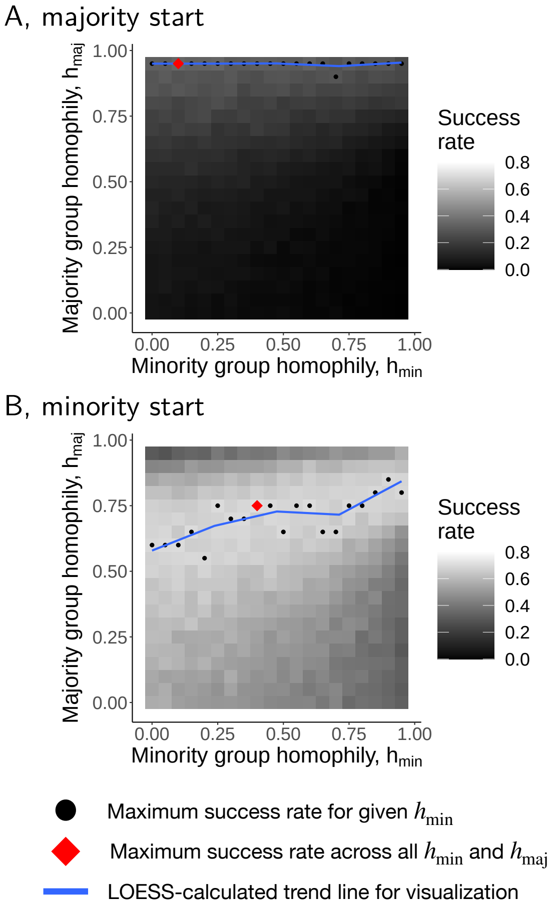
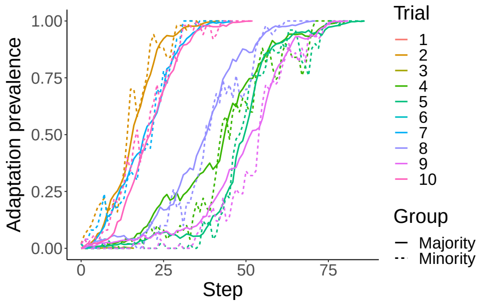


Figure 3: Time series of adaptation prevalence when the adaptation starts in the minority group for two symmetric homophily values, $h_{\text{min}} = h_{\text{maj}} = 0.75$ (A) and $h_{\text{min}} = h_{\text{maj}} = 0.99$ (B). Ten trials shown for each setting, though many trials quickly end in failure.

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



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

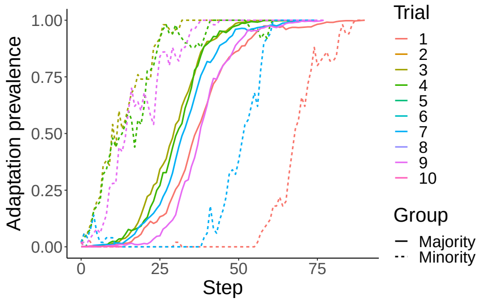
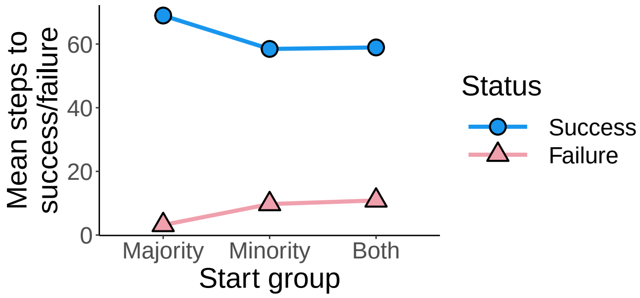


Figure 4: Successful adaptation efforts take significantly longer to achieve on average than failed efforts (mean steps to success or failure on y-axis; group start condition on x-axis). Success happens faster on average when the minority group starts with the adaptation.



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 (Sperber, 1997; Claidière & Sperber, 2007). For example, just as our physical bodies constrain the sort of cultural information humans generate and transmit between individuals in the laboratory (Miton, Wolf, Vesper, Knoblich, & Sperber, 2020), some adaptive traits may be favored due to shared in-group cultural experiences, which could be helpful for amplifying climate change adaptation (Nalau et al., 2018). Complex or taboo adaptive behaviors may require multiple teaching exposures before an individual adopts them (Centola, 2018), but we assumed a single exposure was always sufficient—modifying this single-exposure assumption may result in lower success rates. 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 (DellaPosta, Shi, & Macy, 2015; Yeh, Fogarty, & Kandler, 2019). Furthermore, different traits or behaviors are often composed to form new composite cultural variants through cumulative cultural evolution (Tennie, Call, & Tomasello, 2005; Kirby, Cornish, & Smith, 2008). Group structure is known to co-evolve with cumulative cultural traits (Centola, González-Avella, Eguíluz, & San, 2007; Derex & Boyd, 2016; Derex & Mesoudi, 2020), 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 (Pearson, McNamara, & Nunn, 2020), but it does not help subsistence farmers deal with changing weather patterns in the highlands of these nations.

Our results support the suggestions by Jones et al. (2021) and Pisor et al. (2022) that subsistence, frequently indigenous, populations on the margins of larger more market-integrated populations might be a source of climate adaptation. Moreover, our analysis supports the previous work that suggested successful social innovations start in the peripheries of networks (Steinert-Threlkeld, 2017), rather than in the cores of networks (González-Bailón, Borge-Holthoefer, Rivero, & Moreno, 2011). These observations suggest the potential functional importance of minority group communities for innovation and adaptation. As such, it is essential that minority groups retain cultural autonomy (Pisor et al., 2022). Modeling by Bunce and McElreath (2018) suggests a potential means to support the retention of minority group cultural norms through the construction of protected "homelands," especially when forces toward homogenization are strong. In this regard, our analysis of the efficacy of minority group-initiated adaptations, combined with the results of Bunce and McElreath (2018) on retention of minority norms and the results of Derex and Boyd (2016) on group 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.

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