A data-driven computational model on the effects of immigration policies

Miranda Simon[a,b], Cassilde Schwartz[c], David Hudson[d], and Shane D. Johnson[a,1]

[a]Department of Security and Crime Science, University College London, London WC1H 9EZ, United Kingdom; [b]Department of Political Science, University College London, London WC1H 9EZ, United Kingdom; [c]Department of Politics & International Relations, Royal Holloway University of London, Egham TW20 0EX, United Kingdom; and [d]International Development Department, University of Birmingham, Birmingham B15 2TT, United Kingdom

Many scholars suggest that visa restrictions push individuals who would have otherwise migrated legally toward illegal channels. This expectation is difficult to test empirically for three reasons. First, unauthorized migration is clandestine and often unobservable. Second, interpersonal ties between migrants and would-be migrants form a self-perpetuating system, which adapts in ways that are difficult to observe or predict. Third, empirical evaluations of immigration policy are vulnerable to endogeneity and other issues of causal inference. In this paper, we pair tailor-made empirical designs with an agent-based computational model (ABM) to capture the dynamics of a migration system that often elude empirical analysis, while grounding agent rules and characteristics with primary data collected in Jamaica, an origin country. We find that some government-imposed restrictions on migrants can deter total migration, but others are ineffective. Relative to a system of free movement, the minimal eligibility conditions required to classify migrants into visa categories alone make migration inaccessible for many. Restrictive policies imposed on student and high-skilled visa categories have little added effect because eligible individuals are likely able to migrate through alternative legal categories. Meanwhile, restrictions on family-based visas result in significant reductions in total migration. However, they also produce the largest reorientation toward unauthorized channels—an unintended consequence that even the highest rates of apprehension do not effectively eliminate.

immigration policy | migration | unauthorized migration | computational modeling

Political leaders in many Western countries have called for increased visa restrictions to control immigration. In the aftermath of the November 2015 attacks in Paris, Marine Le Pen declared, "It is essential that France recover the control of its national borders, once and for all" (1). Similarly, one of the main tenets of the Brexit campaign was to "take back control of [UK] borders" (2). In the United States, Donald Trump was propelled to victory with a campaign focused on border control and "extreme vetting" of Muslim migrants. During his early days in office, he moved to change the composition of incoming migrants and reduce flows from family-based and high-skilled channels (3).

But will more restrictive immigration policies stop individuals from migrating? Many scholars suggest that visa restrictions have counterproductive effects, leading individuals to reorient to unauthorized channels (4, 5). While this expectation is prominent in theoretical literature, scholars have struggled to demonstrate it empirically. There are three fundamental empirical challenges. First, unauthorized migration is often unobservable, due to its clandestine and sensitive nature. Even the best estimates of unauthorized migration are extremely limited, are vulnerable to bias, and are often reported only in the aggregate. Second, migration flows do not result from the sum of individual decisions to migrate—they are part of a dynamic and social process. The rich literature on migrant networks holds that interpersonal

ties between migrants and would-be migrants form an adaptive self-perpetuating system. As individual preferences are modulated by the nonlinear effects introduced by social interactions, networks make migration difficult to measure and predict (4, 6, 7). To date, existing research has, generally, been unable to connect decisions and social processes occurring at the micro- and mesolevels to macrolevel trends in migration (8) (however, see ref. 9). Third, drawing causal inferences in empirical evaluations of immigration policy is problematic: Policies are not exogenous and we, generally, cannot observe counterfactual scenarios. Taken together, empirical challenges such as these have led the International Organization for Migration to conclude that, "disregarding the uncertainty and complexity of migration leads to an illusion of control on the part of the decision makers...[and] this is why attempts at managing migration often lead to unintended consequences" (ref. 10, p. 2).

We present a data-driven agent-based computational model (ABM) to examine migration for an origin–destination corridor, which is tailor-made to address these unique empirical challenges. To be clear, our paper does not model all migration into a particular destination. This would require a cross-national data collection strategy. We focus on a single origin country.

Significance

Would more restrictive immigration policies stop individuals from migrating? We present an agent-based computational model, calibrated using original survey and experimental data, which represents an important step in estimating the "substitution effect" whereby migrants reorient toward unauthorized channels due to changes in policy. We find that government-imposed restrictions on migrants can decrease total migration. However, some restrictions are highly ineffective while others decrease legal migration only at the cost of driving migrants into unauthorized channels. Restrictions on students and high-skilled workers are least effective in reducing migration, and restrictions on family-based visas are especially counterproductive in diverting migrants to back channels. We also find that increasing enforcement would not effectively eliminate the diversion to unauthorized channels.

The use of an ABM allows us to simulate migrant reorientation using a generative approach, observing the individual decision making of agents, and more importantly the macrolevel patterns that emerge through their interaction. In building a system, we discretize the migrant's decision into smaller, interdependent components that can be measured empirically and modeled individually. We calibrate the model with an original nationally representative survey conducted in Jamaica, designed to target each of these components using a diverse set of individual indicators and population-based experiments. Through this approach, we capture dynamics of migration systems that often elude empirical analysis, while grounding agent rules and characteristics with unbiased data from an origin country. After demonstrating that the model is capable of reproducing key empirical regularities, we conduct in silico policy experiments, in which we restrict common visa routes, to estimate the counterfactual impact of immigration policies on the volume and composition of simulated (il)legal migrant flows.

Our results suggest that barriers to legal migration can reduce overall migration, but they can also be ineffective or even counterproductive. By far, the largest effects on legal and unauthorized migration result from the imposition of migrant channels. Restrictions to student and high-skilled visas do little to change the volume or composition of incoming migrants. Meanwhile, restricting access to family-based and low-skilled work channels does appear to reduce overall migration. In doing so, however, these changes divert a significant proportion of migrants to back channels. This is particularly true of family-based visa restrictions, which reorient roughly twice as many individuals to unauthorized channels as low-skilled work restrictions. Furthermore, increased enforcement of unauthorized migration will not solve the problem of migrant reorientation. Even very high rates of apprehension coexist with high levels of unauthorized migration. In fact, the effect of increasing enforcement is nonlinear, such that the effect of increasing levels of enforcement on illegal migration is most pronounced when enforcement is already high.

Our paper makes a number of key contributions. ABMs are becoming increasingly prominent in the study of migration (7, 11). This paper attempts to use this method to estimate the "substitution effect" (5) whereby migrants, who would have entered legally, reorient to unauthorized channels due to changes in policy. For policymakers and migrant advocates, we provide suggestions that would reduce unauthorized migration, an outcome which would have important implications for domestic politics and human security. Evidence from the United States shows that legal status is one of the key drivers of antiimmigrant attitudes (12). For migrants themselves, unauthorized status can make for precarious living conditions, submarket wages, and limited access to services and protections from the state. Therefore, it is critical to assess the degree to which visa restrictions can undermine—rather than facilitate—a government's capacity for control.

The Model

ABMs of migration have gained momentum in recent years (e.g., refs. 11, 13, 14), and our model contributes to this nascent field (see ref. 7 for a review). Our model follows guidelines for best practice, which suggest taking seriously the gap between desire and actual behavior, social influence, and the role of uncertainty. They also emphasize the importance of using a decision theory paired with empirical evidence to determine agent rules (7). Decision making in our model is based on random utility theory: Individuals form preferences for migration strategies based on their perceived ability to successfully migrate using that strategy and engage in a nested decision-making process with choice uncertainty. Informed by the psychological literature on heuristics, our agents do not do not base their decisions on full information about policy, but are boundedly rational. Their decision making is based on their own experiential learning and information received through social networks (15, 16).

In the interest of maintaining a clear model purpose and parsimonious design, as suggested by ref. 17, we narrow our theoretical focus to help us identify and understand the effects of immigration policy. As such, our model architecture pulls from a wide range of migration theories that refer specifically to the response of the migrant to immigration obstacles, willingness to consider unauthorized channels, and migrant learning from experience and networks (Table 1).

The literature on barriers to movement maintains that external obstacles (such as policy restrictions) generally result in two outcomes: reduced mobility or undocumented movement. [While many policies affect migration (5), our paper refers specifically to restrictions on entry.] Such obstacles reduce people's perceived ability to migrate through legal channels, but not necessarily their desire to migrate. This generates a gap between aspiration and perceived ability (18–21, 24, 25). As this gap widens, individuals become increasingly likely to migrate through illegal channels (4, 5).

Immigration policies are notoriously complicated and opaque, and individuals are not likely to be perfectly informed of policy changes. Individuals navigate the policy environment through a gradual learning process influenced by their own experience and communication with their networks (14, 19). There is a consensus among scholars that migrant decisions are deeply embedded within social networks (9, 22), and this paper focuses on the role of networks in spreading information about migration policies.

Table 1. Theory and empirical evidence for modeling choices including original data collected for this study (Data source column)

Process	Refs.	Modeling choice	Data source
Adapting to policy	(18–21)	Policy information decreases perceived ability, but not aspiration.	Policy experiment, survey data
Considering unauthorized strategies	(4, 5)	Willingness to consider unauthorized strategies increases as the gap between ability and aspiration to migrate increases.	List experiments, survey data
Learning	(9, 14–16, 22, 23)	Successful past migration and successful migration of networks increase perceived ability. Past failures to migrate decrease perceived ability to migrate.	Survey data

These theories of migrant behavior, the effects of policy restrictions, and the dynamic nature of learning provide an overarching theoretical framework from which we develop our model and corresponding agent rules. However, ABMs are often criticized for being constructed based on an unfalsifiable set of rules and assumptions. We tackle this critique explicitly by testing our key assumptions empirically before model construction. Theoretically motivated model processes and associated empirical evidence are summarized in Table 1 (also *SI Appendix*, section C.1). For modeling choices we could not test empirically, we conducted sensitivity analyses, the results of which can be found in *SI Appendix*, section D. The aim of the model is to establish the process by which individuals who are motivated to migrate interact with policy restrictions by adopting alternative strategies: migrating legally or through unauthorized means or, alternatively, choosing to stay home. In the following sections, we describe each stage of our model, illustrated in Fig. 1, in detail. Additionally, *SI Appendix*, section A provides a low-level description of model processes and associated pseudocode.

Initialization. Our ABM consists of an environment, which represents an origin country, autonomous agents, and condition action rules that guide agent behavior (17). Each agent is allocated a profile of characteristics belonging to an individual respondent from an original survey conducted in Jamaica. Modeling always involves some trade-offs. Our survey data are cross-sectional, and we operate under the assumption that agents do not change over time and are not replaced if they migrate. (*SI Appendix*, section D.3 presents sensitivity tests where we allow agents to change their preferences as they age.) This allows us to maintain the correlation structure of our data, as realistic demographic profiles are essential in determining agent eligibility for specific visa channels. Also, informed by trends in the literature and our survey finding that over 90% of our sample was committed to a single destination country, we depict a single corridor. In line with our model purpose, the destination country is abstract of all characteristics aside from its policy profile.

Concurrent with extant work (26), social tie formation is modeled as a function of agent similarity (homophily) and geographical distance (*SI Appendix*, section A). We do not make assumptions on the types of relationships agents have with one another. We consider the duration of a migration decision, from

an initial desire to migration attempt, to be 1 y, following theoretical evidence (27, 28) and estimates on immigrant visa processing times. As agents' actions are dependent on those of others, agent variables are updated synchronously at the end of a procedure (17). This ensures that the only factor limiting agents' access to information from agents at home and abroad is the boundedness imposed by network structure and not the time at which the agent is called to act (and how much information it was able to accumulate up to this point). This design mimics information seeking in uncertain decision scenarios, of which international migration is an example (see *SI Appendix*, section A.2.2 for more details on time and scheduling).

Individual Decisions. To engage in migration, individuals must both desire and perceive themselves capable of migrating (18–21). This model focuses on voluntary migration. In our sample, aspiring migrants are defined as those surveyed who would like to migrate at least "a little" and have considered migrating at least "quite seriously."[†] As such, desire to migrate, D, is defined by the intersect of two variables: L, "like," and S_e, "seriousness" (see Table 2 and *SI Appendix*, section B for more details on variable scales). As such, absent the desire to migrate, agents choose to stay home. If they wish to migrate, individuals choose a channel. Most broadly, there are two types of migratory channels: legal and unauthorized. We denote all strategies or channels as S, where $\{S_{leg}, S_{unauth}\} \subset S$. Legal channels include the most common visas (*SI Appendix*, sections B.3 and E provide further details on unauthorized and legal migration channels, respectively). The vast majority of migration literature tends to downplay the wide variation that exists within unauthorized migration, but case studies show a wide spectrum of strategies differing in terms of legal costs and less tangible, normative barriers. We draw on this literature to distinguish between full noncompliance, or strategies that circumvent immigration law entirely (e.g., migrating with no documents or fraudulent documents), and semi-noncompliance (e.g., strategies where migrants obtain legal documents but violate migratory restrictions) (29–32). (Salient examples of semi-noncompliance include "visa overstaying" or working on a tourist visa. See *SI Appendix*, section B.3.1 for a full conceptualization of these strategy types.) This distinction helps us to model the legal and normative barriers of unauthorized migration more accurately.

Agents evaluate their willingness to consider each unauthorized strategy separately because it is possible that they will be willing to consider one, but not the other. Not all migrants will be willing to consider one or either of these strategies for normative reasons (33). Individuals are more likely to consider unauthorized channels as the gap grows between their desire to migrate, D, and their ability to migrate legally, A_{leg} (4, 19). Therefore, the probability that agents will be willing to consider each unauthorized option, $\theta_{S_{unauth}}$, is conditional on this gap (for an empirical test, see *SI Appendix*, section C.1.2). This process creates the individual's strategy choice set.

Each agent has a different perception of his or her ability to migrate through a given channel. Agents choose the (legal, semilegal, or illegal) strategy they will attempt, S^*, through a weighted random draw, with each strategy weighted by the agent's perceived ability to execute it. (Note that the strategy set may be reduced if the agent is unwilling to consider one or both
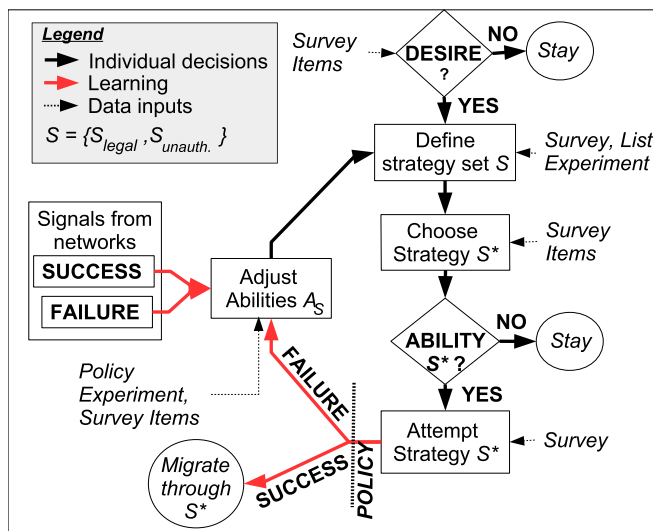

Fig. 1. System diagram showing agent decisions, feedback processes, and data types used for calibration.

[†]We decided to include those who would like to migrate a little because the cutpoints between items in an ordinal scale are often highly subjective and subject to noise. As such, we considered any response in the affirmative direction of our bipolar scale as a positive statement of aspiration. Alternatively, we could have defined aspiring migrants as those who would like to migrate at least a "moderate amount." This would have reduced the subset by only 45 agents.

Table 2. Data collected or used to calibrate the model

Type	Variable/estimate	Values	Source
Individual variables vary across agents	Desire to migrate, $D = L \cap Se$	$1 \leq L \leq 7$; $1 \leq Se \leq 4$	Survey item
	Ability to execute a strategy, A_S $S = \{$Legal, semilegal, illegal$\}$	$1 \leq A_S \leq 7$	Survey item, endogenously updated
	Visa eligibility demographics, α_d: $d = \{$education, sector, income, family$\}$	$1 \leq \alpha_e \leq 8$; $\alpha_s = \{0, 1\}$ $0 \leq \alpha_i \leq 2,130$; $0 \leq \alpha_f \leq 20$	Survey items
Aggregate effects, fixed	Effect of receiving policy information (positive/negative), π	$\pi = \pm 0.55$	Policy experiment
	Effect of gap in aspiration and ability on $\theta_{S_{ill}}$	$\beta_{illegal} = 0.05$; $\beta_{semi} = 0.04$	List experiment
Policy varies by model setting	Probability of avoiding border detection, r	$0 \leq r \leq 1$ (Figs. 3–5: $r = 0.30$)	Survey item
	Probability of successful semilegal migration, p	$0 \leq p \leq 1$ (Figs. 3–5: $p = 0.32$)	US State Department, survey item
	Visa quotas, v_q {high skilled, student, low skilled, family}	$0 \leq v_q \leq 1$	Department of Homeland Security Yearbook, survey items

See *SI Appendix*, section B for more details on data (including experiments) and descriptive statistics. Table 2 shows policy settings for the validation model. Details on policy values for in silico experiments can be found in Table 3 and in *SI Appendix*, section E. Income is in US dollars. p is a product of visitor visa acceptance rates and internal enforcement. See *SI Appendix*, section B.2 for details.

of the unauthorized strategies for normative reasons.) The agent will attempt S^* only with a probability $P(Attempt)$ defined by

$$P(Attempt) = 1/1 + e^{(k(T - A_{S^*}))}, \qquad [1]$$

where T is the middle category in our seven-point ability scale (*SI Appendix*, section B.2) and k is the curvature of the logistic function. For the remainder of this paper we leave k at 1, but present results for alternative specifications of k in *SI Appendix*, section D.2. When we compare simulation results to official data sources, we find that while k affects overall levels of migration, it does not substantially change its legal composition (*SI Appendix*, section C.2).

An agent's perceived ability to migrate may or may not coincide with current policy conditions.[‡] If an individual has chosen to attempt a legal strategy ($S^* = S_{leg}$), he or she will evaluate the demographics according to the requirements of the receiving state. Common legal migration routes include student, low-skilled, high-skilled, and family-based visas. An individual may be prevented from migrating legally simply because he or she does not meet the classification criteria for any legal categories (hereafter, baseline eligibility criteria). For instance, an individual with no family abroad cannot migrate through family reunification, regardless of quotas or restrictions. We define the set of legal migration categories for which a given migrant is eligible as V_i, where $V_i \subset S_{leg}$. In addition, a series of requisites and quotas may be placed on each of the channels exogenously, thereby excluding otherwise eligible individuals.

We assume agents are indifferent about available legal channels. That is, if the individual's optimal migration strategy is legal migration, he or she will migrate legally if eligible for at least

one visa. If individuals are eligible for more than one visa, they may shift across available visa options. These agents can migrate through alternative legal means if policies change.

For agents whose optimal strategy is an unauthorized one, the rules are much simpler. The overall probability of success through each of the two unauthorized strategies is applied uniformly. Individuals will migrate if they successfully avoid enforcement. In real life, undocumented migrants may regularize their status in the destination, or legal migrants may become undocumented after entering legally. As our model focuses exclusively on migrant entry, the model does not make assumptions or generalizations about shifts in legal status.

In a simulated year, an individual may attempt only one strategy S, legal or otherwise, to account for the time necessary to prepare for migration, possibly through an alternate channel, in the next year. Agents that have migrated are excluded from subsequent model processes, but influence the decisions of their network.

Interaction and Learning. Potential migrants are not immediately or uniformly aware of immigration policies; they learn through interaction with immigration authorities and the experiences of others. In our model, agents update their perceived ability to migrate by aggregating this information.[§] Specifically, individuals accumulate information from their network contacts, η_j, and from their own experiences, η_i. These signals are strategy specific and may be positive or negative. For simplicity, we assume all information sources affect agents' perceived ability to migrate through any strategy by the same magnitude, π. Tests examining the effects of alternative weights on positive and negative signals, as well as signals obtained directly and indirectly, are provided in

[‡]A 2013–2016 Gallup poll found that 14% of the world's population wished to migrate (34). However, international migrants make up only 3.3% of the world's population (35). By discretizing the migrant decision-making process into various stages—i.e., aspiration to migrate, perceived ability to migrate, and migration attempts—we contribute to the important literature on the "aspiration–behavior gap" in migration (21, 25, 36).

[§]Perceived ability to migrate is dynamic, but aspiration is not. This assumption is based on experimental evidence on the effects of policy information, shown in *SI Appendix*, section C.1.1. Our empirical analysis shows that varying aspiration as a function of age does affect individuals' aspiration to migrate. However, sensitivity tests in *SI Appendix*, section D.3 show that programing aspiration as a function of age does not significantly affect model outcomes.

SI Appendix, section D.1. The impact of omitting network effects is also explicitly examined.

We define C to be the unique effect of the cumulative information an individual obtains from network contacts, η_j, on their ability to migrate through a given strategy. We assume each additional signal about the policy environment has a decreasing marginal effect on agents' perceived ability to migrate through that strategy. Following established literature on the learning curve (37, 38), we take the natural log of the sum of contacts, $j \in J$, who relay an experience with immigration policy. Agent i computes C separately for positive (C_+) and negative (C_-) information at time t. The only difference is the direction of π:

$$C_{i,\pm}^t = \pm\pi\left(1 + \log\sum_{j=1}^{J}\eta_j\right). \quad [2]$$

Individuals also learn from personal experiences with immigration policy. These experiences are necessarily negative, as a positive experience would entail a successful migration, after which no learning is necessary. We define B as the unique effect of an agent's own experience with immigration policy on the ability to migrate through a given strategy. Similar to Eq. **2**, we consider the effect of one additional migration failure, f, for agent i, to be marginally decreasing:

$$B_i^t = -\pi\left(1 + \log\sum_{f=1}^{F}\eta_{i,f}\right). \quad [3]$$

Finally, each simulated year, agent i updates its ability to migrate for each strategy S as

$$A_{i,S}^t = A_{i,S}^{t-1} + \Delta B_i + \Delta C_{i,+} + \Delta C_{i,-}, \quad [4]$$

where $A_{i,S}^t$ is censored to maintain the range of the original survey scale. Two main sources of stochasticity affect the learning process. First, the network connections determining who the agent is able to learn from are determined probabilistically (*SI Appendix*, section A.1.2). Second, stochasticity is incorporated into exogenous restrictions on legal and unauthorized channels, thereby affecting the successes and failures that agents learn from through personal experience and their networks. This is detailed later in this paper.

Empirical Calibration and Validation. We calibrate the model using data from an original survey conducted in Jamaica. This Caribbean island has a historically high propensity for voluntary migration and therefore increases the probability that aspiring migrants will be included in our sample (39). While there are countries with similarly high rates of aspiring migrants, Jamaica is a particularly illustrative case because only a very small proportion of these emigrants qualify as forced migrants (*SI Appendix*, section B.1). We expect that individuals who are being forced from their homes are likely to make migration decisions under heightened constraints compared with other aspiring migrants. Although we collect data from a specific origin country, the behavioral rules developed and presented in this paper are simple and grounded in migration theory and, therefore, generalizable to other cases of voluntary migration.

Our survey was fielded between April and June 2016. Jamaica is subdivided into 14 large administrative units called parishes and our sample includes all 14 parishes on the island. In total, our sample consists of 1,166 face-to-face interviews with Jamaican adults from across the island. The ethics board of University College London (application no. 7045/004) approved all data collection procedures relating to the survey and experiments. All experiments involving human subjects were approved by the ethics board of University College London. Informed consent was obtained by respondents before participation. All data and replication materials can be found at https://dataverse.harvard.edu/dataverse/unauthabm.

We designed this survey to precisely identify the independent components of the migrant decision and integrate them into a dynamic model of migration. We measure aspiration and ability to migrate as distinct indicators and operationalize perceived ability to migrate as strategy specific. We also measure support for unauthorized strategies separately from the perceived ability to migrate through unauthorized channels. Table 2 shows the types of data collected and Fig. 1 illustrates where they feed into the model. More information on our survey and specific items can be found in *SI Appendix*, section B.

There are many reasons why an individual may aspire to migrate (e.g., perceived earning potential or images of a foreign country portrayed by the media) or feel able to (e.g., having sufficient funds). Our model does not seek to identify individual migration determinants, and we assume our survey indicators for aspiration and perceived ability capture these antecedents.

Two important model variables that pose unique measurement challenges are the influence of policy on migrant decision making and support for unauthorized migration. To estimate the effects of policy information on perceived ability to migrate, our survey contained an embedded experiment. Participants were randomly assigned to view a video about the real difficulties (imposed by policy) Jamaicans may face when attempting to migrate or a control condition. Policy effects were estimated by computing between-group differences in participants' perceptions of their ability to migrate (see *SI Appendix*, section B.4 for experimental protocol and *SI Appendix*, section D.1 for alternative model specifications).

Standard survey questions on unauthorized migration are impeded by social desirability bias. Consequently, we use a between-subjects list experiment to estimate support for each strategy (40). This design protects respondents' anonymity on sensitive items. Here, respondents receive a list of possible migration strategies and are instructed to reveal only the number of strategies they would support, but not which ones. The treatment list includes an unauthorized migration strategy and the control list does not. A simple difference in means provides an estimate of support for the unauthorized strategy (*SI Appendix*, section B.3.2). We include two independently randomized list experiments to measure support for both classes of unauthorized strategies (illegal and semilegal).

To demonstrate that our model generates meaningful patterns of migration, we use a two-stage strategy to test model quality. First, we assess the model's condition action rules through empirical tests of intermediate processes (e.g., do agents adjust their ability to migrate when receiving a policy signal?). These tests are listed in Table 1 and *SI Appendix*, section C.1 contains the details and results of these tests. (*SI Appendix*, section D reports additional sensitivity tests.) Second, we validate model outcomes, testing for agreement with empirical data from official sources. We find that our model approximates real migrant volume, composition with regard to legal status, and migrant learning (*SI Appendix*, section C.2). For these tests, we set our model's policy conditions to match those of the United States for a fixed set of years. In our comparisons of migrant volume and composition, we use independent data from the Jamaican census and the US Census Bureau. In our comparison of migrant learning, we use survey data not used in model calibration.

Experimenting with Policies

ABMs allow us to isolate components of a policy package and test their interactions, enabling controlled experiments that would be impossible in real life. Our experiments examine restrictions on students, high-skilled workers, and low-skilled

workers, as well as individuals who migrate to join family members abroad. Additionally, we examine a policy of free movement and a scenario where all of the channels mentioned are restricted. Please see *SI Appendix*, section E for further references on the details below.

Early Departures for International Students. Student migration has become politically problematic in many countries. To reduce student migration, many governments restrict the opportunities available to them after graduation. For example, one of the 2015 United Kingdom General Election commitments was a net reduction in migration to under 100,000, and in 2014, students made up the largest share of the non-European Union migrant population. The United Kingdom closed its poststudy work route to new applications from non-European Union students in April 2012. In our model, agents who intend to work or save money while abroad will no longer be able to migrate if this option is restricted.

Closing Doors to High-Skilled Workers. Many politicians suggest that high-skilled jobs should prioritize native workers over foreigners. During his campaign, Donald Trump said, "I will end forever the use of the H1-B as a cheap labor program, and institute an absolute requirement to hire American workers first …No exceptions." (41). In the United Kingdom, a recent proposal from the immigration minister would introduce a £1,000 levy on employers for each European Union skilled worker recruited after Brexit. Because these penalties are imposed on the employer rather than the potential migrant, we operationalize high-skilled work restrictions as a quota applied uniformly to all agents who meet eligibility conditions for that channel.

Caps on Low-Skilled Workers. Many countries implement quotas or caps on the number of low-skilled migrants admitted. Often, these are sector specific, and employers recruit only for sectors with the greatest domestic need. After the United Kingdom voted to leave the European Union, the immigration minister was quick to propose sector and country caps to regulate and bring down low-skilled migration. Consequently, we use quotas to restrict eligible agents in our in silico experiments.

Thresholds for Family Reunification. Through family reunification visas, migrants may apply to have their family members join them in the destination country. After Donald Trump was elected, Republican senators proposed strict limits on these visas, hoping that migrants would reorient toward employment channels. This proposal included limiting sponsorship to spouses and young children, while imposing requirements for background checks and proof of financial support. The family reunification channel is often restricted through requirements placed on the resident migrant. In the United States, for example, sponsors must demonstrate that they can financially support their family and the incoming arrival at an annual income 125% above the poverty line. A similar threshold applies in the United Kingdom. Income information about family abroad is not necessarily observable for individuals at the origin country. However, the length of their absence is observable and is also a well-established indicator of migrant earnings (e.g., ref. 42). It is worth noting that there is considerable variation in earnings trajectories across migrant groups. West Indian men are significantly disadvantaged when it comes to earnings relative to foreign whites (42).

Free Movement. In theory, free movement of people represents the absence of migratory channels. Individuals who desire to move abroad would be able to do so without government-imposed restrictions. Free movement of people is one of the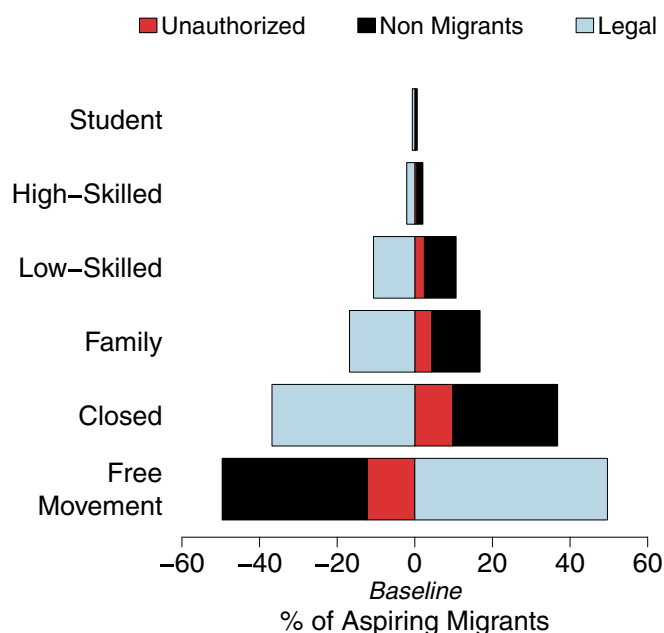 main pillars of the European Union. All European Union citizens can reside in any country within the Union for up to 3 mo and may stay for longer if they fulfill basic conditions. To shift from a policy of free movement to one with restrictions, a government would likely define and impose migrant channels. The United Kingdom, upon leaving the European Union, will find itself in this position.

Fig. 2. Mean effects of policy restrictions on migration outcomes relative to the baseline setting (where $x = 0$).

Results

In our first set of experiments (Figs. 2–4), we compare migration patterns to a baseline setting. Our baseline setting classifies agents into common migrant channels absent of quotas and requirements, which can additionally be imposed by the host government. Classifying potential migrants into these channels has its own effect—limiting migration among individuals who are not eligible (Table 3). Thus, by comparing each policy setting to the baseline, we isolate the unique marginal impact of quotas and restrictions among eligible migrants. In Fig. 2, we fully restrict one channel at a time. We then focus on the two visa routes that produced the most substantial reorientation in these experiments, to observe the effects of more gradual increases in these policy restrictions. In Figs. 2–4, we maintain a constant level of enforcement for unauthorized channels (see *SI Appendix*, section B.2 on calibration of this value). Therefore, we conclude with experiments that vary levels of enforcement for all immigration policy settings.

We report the results at the end of 20 simulated years, as agent learning about entry policies consistently stabilizes around that time (*SI Appendix*, section F). For each simulation run, we compute the migrant stock accumulated across all simulated years. All our figures present the mean across 1,000 runs.

Each bar in Fig. 2 shows changes (as a percentage of aspiring migrants) from the baseline conditions in terms of legal migration (blue), unauthorized migration (red), and nonmigration (black). Unauthorized migration includes illegal and semilegal categories. In the baseline setting, agents may migrate if they are eligible for any of the four visa channels (Table 3). In this condition, approximately 44% of aspiring migrants migrate through legal channels, 18% migrate through unauthorized channels, and 39% do not migrate. This shows that the mere existence of migratory categories excludes many would-be migrants.
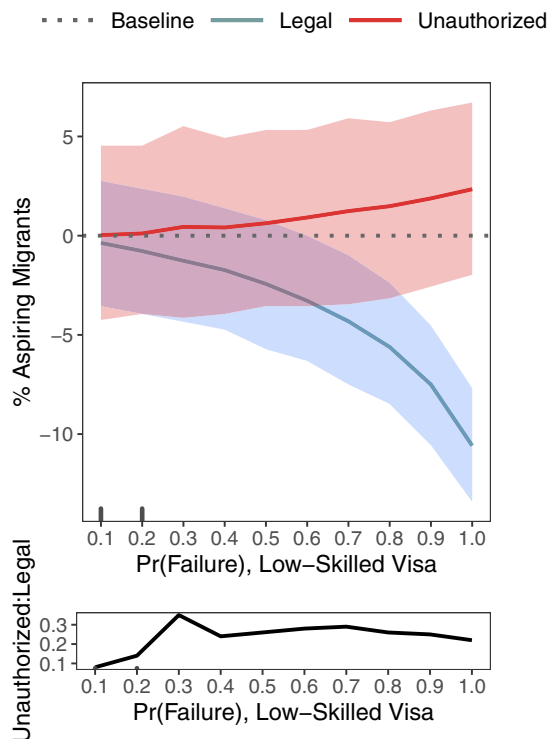
Fig. 3. Mean effects of restricting low-skilled work visas on migration outcomes relative to the baseline with 2.75th and 97.5th percentile error band and ratio of unauthorized to legal migration. The rug line on the *x* axis indicates the model settings where the level of unauthorized migration is not significantly different from the level of unauthorized migration in the baseline setting.

As is shown in the top two bars of Fig. 2, full restrictions on students or high-skilled workers lead to negligible changes in migration outcomes. Fig. 2 indicates that full restrictions on student visas lead to 0.64% fewer aspiring migrants entering legally and a corresponding 0.51% and 0.13% more aspiring migrants opting not to migrate and migrating through unauthorized channels, respectively, compared with the baseline eligibility model. Closing off the high-skilled work channel leads to a very small percentage of aspiring migrants opting for the unauthorized route (0.54%) and a similarly small, 1.54%, increase in nonmigration. These findings are rooted in the fact that individuals in many developing countries, like Jamaica, are often not eligible for these channels even in baseline conditions. Hence, additional quotas or restrictions on these channels will have little to no effect on migration.

Next, we examine full restrictions on low-skilled visas and family-based visas. In Fig. 2, we see that closing off the low-skilled route would lead to 10.64% fewer aspiring migrants entering legally than would have done in baseline conditions. Instead, 2.50%, or approximately one-quarter of these individuals, will opt for unauthorized migration, with the remainder not migrating. Compared with migration levels in the baseline setting, closing off the low-skilled channel leads to a 13.73% growth in unauthorized migration and a 21.23% growth in nonmigration.

When the family route is closed, 16.82% fewer agents enter legally, as a percentage of aspiring migrants. This shift corresponds with a 12.46% decrease in migration among aspiring migrants and a 4.36% increase in unauthorized migration. In other words, approximately 26% of the individuals prevented from migrating legally as the family reunification channel is closed reorient to unauthorized channels. Compared with migration levels at the baseline, closing the family route results in a

32.35% growth in nonmigration and a 24.25% growth in unauthorized migration levels. Unauthorized migration in this setting grows at more than double the rate of the low-skilled setting.

Reorientation to unauthorized channels is so high when family reunification channels are restricted because the family-based channel is most easily accessible at the baseline level, as Jamaica's vast diaspora is helpful in continuing migrant flows. This is often the case for countries with a long history of migration. Eligibility for low-skilled work permits generally requires prior work experience in a high-demand sector, making this channel less accessible than the family route.

Finally, we consider two opposing scenarios: one in which all legal channels are fully restricted (the closed scenario) and one in which we remove migratory channels completely (free movement). In Fig. 2, we see that, relative to the baseline setting, closing all channels would increase unauthorized migration by 9.76% and nonmigration by 27.04%. As a percentage of all aspiring migrants, the free movement setting decreases unauthorized migration by 12.27% and increases legal migration by 49.64%. If a country removed immigration channels in favor of free movement, total migration would increase substantially, but unauthorized migration would also decrease substantially. It is noteworthy that the removal of migratory channels has the largest influence on migration of all of the policy settings examined. In effect, minimal baseline eligibility conditions are so restrictive that removing them changes the volume and composition of migration far more than even the most draconian policy restrictions, as shown in a comparison of the closed and free movement settings.

In Figs. 1 and 2, we examined the effects of fully restricting visa routes. Of all visa channels considered, low-skilled and family restrictions produced the most substantial reorientation toward unauthorized channels. In Figs. 3 and 4 we examine the relationship between policy restriction and reorientation by looking at gradual increases in low-skilled and family restrictions. Figs. 3
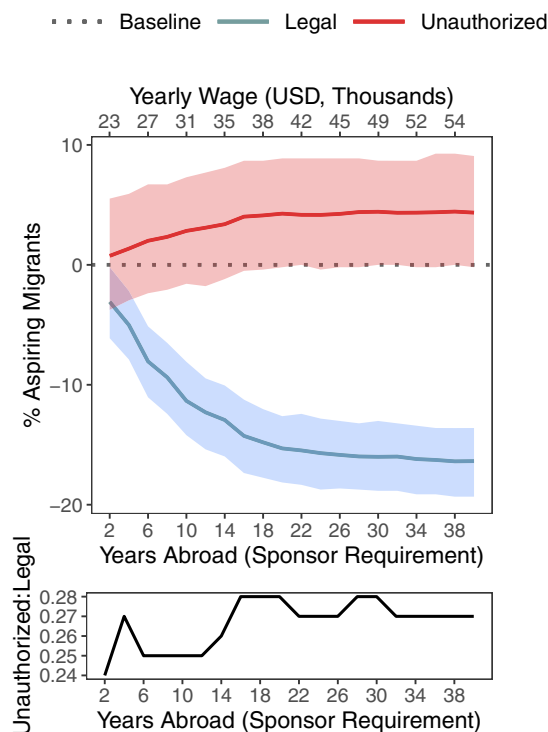

Fig. 4. Mean effects of restricting family reunification channels on migration outcomes relative to the baseline with 2.75th and 97.5th percentile error band and ratio of unauthorized to legal migration.

Table 3. Agent eligibility and thresholds for visa categories

Visa category	Baseline eligibility conditions	*%eligible*	Additional restrictions
Student	Secondary school, 90th percentile household income	16	Accept only those who do not intend to earn or save money abroad
High-skilled work	University degree	10	Accept a fixed % (quota) eligible for this visa at the baseline (randomly selected)
Low-skilled work	Experience in agriculture, construction, or transportation	18	Accept a fixed % (quota) eligible for this visa at the baseline (randomly selected)
Family reunification	At least one family member living abroad	58	Accept only those who have a family member living abroad for a fixed set of years
Closed	None	1.7	Aggregation of above
Free movement	None	100	Accept all

The student channel cannot be entirely closed, as individuals can still migrate as students if they do not intend to earn or save money abroad. This accounts for the small percentage of agents who can migrate in the closed setting.

and 4 present the migrant stock accumulated across all 20 simulated years, averaged across 1,000 runs. The error bands in Figs. 3 and 4 represent the 2.75th and 97.5th percentiles for each level of restriction.

Low-skilled visa restrictions are operationalized as quotas or the probability of failing to receive a visa. In practice, an agent eligible at the baseline draws a number from a random uniform distribution. If this number is larger than, for example, 0.1 (10% quota), the agent is not granted a visa. This amounts to approximately 90% of agents not being able to get a low-skilled work visa in this example.

Fig. 3 gradually increases the probability of failing to secure a low-skilled work visa, compared with the baseline, at intervals of 0.1. This, in effect, estimates the impact of low-skilled work quotas among eligible agents. As we increase the low-skilled visa quota, the percentage of aspiring migrants migrating legally declines at what appears to be a much steeper rate than unauthorized migration. A closer examination shows that for the most part, we see relatively stable levels of unauthorized migration as a proportion of would-be legal migration—approximately one-third. However, as the quota becomes highly restrictive (Pr(Failure) = 0.7), we begin to see the ratio of unauthorized to would-be legal migration decrease to less than one-quarter (2.34%/10.58%). In other words, highly restrictive quotas (Pr(Failure) $\geq$ 0.7) on low-skilled work decrease legal migration at a much greater rate than they increase unauthorized migration.

We also run a one-sided Mann–Whitney test for each setting of Pr(Failure), considering an alpha value of 0.05 to examine whether average unauthorized migration is statistically different from the baseline. We find significant differences at all levels of Pr(Failure) larger than 0.2. In Fig. 3, insignificant differences are indicated with the presence of a rug line above the *x*-axis tick. We do not report the Mann–Whitney tests on legal migration, as legal migration is significantly different from the baseline at every level of Pr(Failure). Although legal and unauthorized migration means across runs are distinct, the error bands spanning the 2.75th and 97.5th percentiles show a large overlap. Significantly higher levels of unauthorized migration at all intervals of Pr(Failure) $\geq$ 0.2 are confirmed by a one-sided Mann–Whitney test.

As mentioned above, governments often restrict family migration by placing income requirements on sponsors. Although we cannot vary income requirements, "years since migration" (YSM) is a strong predictor of migrant income. Upon arrival,

migrants generally earn less than native-born citizens, but incomes rise rapidly with labor market experience. Studies of immigrant labor market adjustment have shown that immigrant incomes tend to equal or surpass native counterparts after a period of 10–15 y (42, 44). As such, we can approximate a wage level with which each YSM requirement corresponds. We use US wages, as the United States is the primary destination for Jamaicans, but we should expect trends to be generalizable to other destinations too (e.g., ref. 44).

Fig. 4 shows the effect of restricting the YSM requirement for potential family sponsors compared with the baseline. To migrate through this channel, an individual must have at least one family member who has lived abroad for a number of years larger than or equal to the YSM requirement, as captured by our survey data (at the baseline, the YSM requirement $\geq$0). Fig. 4, *Top x* axis represents the wages accumulated in 2015 among American Community Survey respondents born in Jamaica living in the United States for the corresponding number of years (45). These data show wages rising consistently before reaching a peak at YSM $\geq$ 48. Wage values displayed in Fig. 4 are estimated using local polynomial regression (*SI Appendix*, section E).

Restricting family sponsorship requirements from 2 y to 18 y—which corresponds to estimated wage levels between US$23,000 and US$38,000—appears to have the largest effect in reducing legal and driving up unauthorized migration, compared with baseline conditions. This trend becomes relatively flat with sponsorship thresholds corresponding to yearly wages higher than US$38,000. At a 2-y YSM requirement (corresponding to an earnings threshold of $\approx$US$23,000), legal migration as a percentage of aspiring migrants is 3.08% lower compared with the baseline. This corresponds with a 0.75% reorientation of aspiring migrants toward unauthorized channels. At a 10-y restriction ($\approx$US$31,000), almost 3% of aspiring migrants have reoriented toward unauthorized channels. At an 18-y restriction ($\approx$US$38,000), 14.8% of aspiring migrants who would have entered legally under baseline conditions are no longer doing so. Approximately 28% of these individuals are now adopting unauthorized channels. After this point, further restrictions have only subtle effects on the composition of migrants. Across the full range of settings, relative to the baseline, the ratio of unauthorized to legal migration oscillates around 0.26, increasing marginally from the lowest setting to larger values (Fig. 2). We run a one-sided Mann–Whitney test comparing each setting of YSM to baseline conditions and find levels of unauthorized
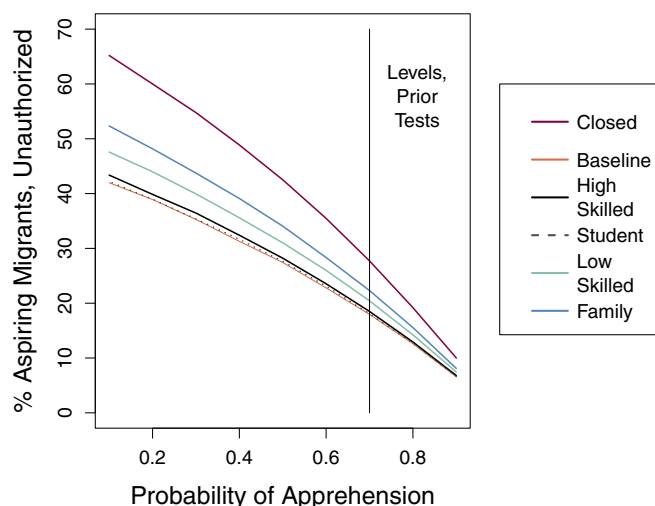
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Fig. 5. Mean effect of increasing levels of enforcement on unauthorized migration.

migration in all settings are significantly greater than the baseline. Legal migration is significantly different from the baseline at every level of YSM.

The experiments shown above vary policy settings for legal channels but use a constant level of enforcement. However, some might argue that the threat of unauthorized migration could be reduced by enforcing border controls or increasing apprehension rates. Fig. 5 shows that this may not be very efficient. In this experiment, we varied the rate of apprehension for both unauthorized strategies jointly from 10% to 90% and show the percentage of aspiring migrants who migrate through unauthorized means for each policy setting presented in Fig. 2, except for the free movement setting. Unlike Fig. 2, these results are not subtracted from the baseline. (We do not include the free movement setting because it is impossible to migrate through unauthorized channels in a setting where, strictly speaking, migrants can cross the border freely.)

For all policy settings, the percentage of aspiring migrants entering through unauthorized channels (including full noncompliance and semi-noncompliance) remains quite high even at the very highest levels of enforcement. For instance, when authorities are able to capture 7 out of 10 unauthorized migrants, we see approximately 27.71%, 22.30%, and 20.43% of aspiring migrants migrating through unauthorized channels for the closed, family, and low-skilled settings, respectively. At lower levels of apprehension, for example probability of apprehension = 0.5, more than one-quarter of all aspiring migrants use unauthorized channels for all policy settings. When all legal channels are fully restricted (the closed setting), 42.52% of all aspiring migrants enter the destination country through unauthorized channels.

The effectiveness of apprehension is nonlinear. In the baseline setting, increasing the rate of enforcement from probability of apprehension = 0.1 to 0.5 decreases unauthorized migration by 14.63%, but increasing the rate of enforcement from probability of apprehension = 0.5 to 0.9 decreases unauthorized migration by 20.76%. In the closed setting, unauthorized migration decreases by 22.68% when apprehension increases from 0.1 to 0.5, but decreases by 32.52% when apprehension increases from 0.5 to 0.9. The greatest gains can be made when governments capture more than 6 of 10 unauthorized migrants, an ambitious number when one considers the volume of unauthorized migration and the diverse forms it can take.

Fig. 5 also shows that if enforcement of unauthorized migration is 80–90%, levels of unauthorized migration tend to converge across all policy settings. That is, strictly speaking, when

levels of enforcement are sufficiently high, the visa policy restrictions have little effect on the rate of unauthorized migration. This suggests that more than 80% of all unauthorized migrants would have to be apprehended to account for the increased reorientation of stringent policy restrictions.

Discussion

We build a theoretically informed and data-driven ABM of migration that simulates the effects of immigration policies, allowing us to observe the reorientation of flows toward unauthorized channels when legal channels are restricted. We find that government-imposed restrictions on migrants can decrease total migration. However, some restrictions are highly ineffective and others decrease legal migration only at the cost of changing the balance of legal and unauthorized migrants. The impact of immigration policy depends on the specific restriction imposed. Policies that prevent students or high-skilled workers from migrating legally have little effect because eligible individuals are likely able to migrate through alternative legal categories. Meanwhile, restrictions on family-based visas produce the largest reductions in total migration and, simultaneously, the greatest reorientation toward unauthorized channels. Restricting low-skilled work reduces total migration to a lesser extent than family-reunification restrictions, but the rate of reorientation to unauthorized channels is also much lower. We also find that, relative to a system of free movement, the minimal eligibility conditions required to impose migratory channels are highly restrictive on their own.

We find that unauthorized migration remains quite high even at the highest rates of apprehension. This relationship is nonlinear; the most substantial reductions in unauthorized migration occur at very high rates of enforcement. These findings are consistent with recent empirical literature, which has found increases in border enforcement in the United States to be highly ineffective at reducing unauthorized migration (46).

This model represents an important step in using data-driven ABMs to observe "substitution effects," whereby potential migrants, who would have migrated legally, migrate through unauthorized means due to changes in policy. In the current context where measures and predictions of migration, particularly unauthorized migration, are based on highly imperfect data and estimation techniques, we believe that our approach could be used to answer questions that have heretofore eluded empirical investigation.

Our findings suggest a number of avenues for future research. First, we look to calibrate the model using data from new contexts. Results will likely vary across countries with different migration histories and diaspora abroad or across countries where individuals have greater access to legal channels or where fewer individuals aspire to move abroad. We could consider the case of Mexico, for example. Mexican citizens tend to have much lower intentions to live or work abroad than Jamaicans (47), but are also generally wealthier (gross domestic product per capita is almost double that of Jamaica) (48), and therefore will likely have a relatively higher ability to migrate legally. At the same time, the well-established tradition of *coyotaje*, or the hiring of smugglers, may also make unauthorized migration from Mexico easier and more accessible (49). Likewise, we could examine Indian migrants, who represented the highest proportion of high-skilled visas and the second-highest proportion of student visas to the United States in 2016 (50). These circumstances are notably distinct from those of Jamaican migrants, for whom high-skilled and student visas are largely inaccessible.

Additionally, the model could explore the conditions under which individuals may adapt by changing destination countries, instead of changing channels (5). This is a potentially important and relatively understudied behavioral response to policy change. Also, subsequent models may expand their scope beyond

migrant entry, allowing for undocumented migrants to regularize their status in the destination or for legal migrants to become undocumented after entering legally. These models will also look to incorporate return migration, as reverse flows are also affected by government policy. Several studies on the Mexico–US corridor have shown that increased border enforcement has turned temporary migrations into permanent ones as migrants will often stay abroad if they fear facing another risky crossing in the future (46).

We also look to examine the endogeneity of immigration policies. While this paper examines how migration flows respond to immigration policies, policies also respond to migration flows. In 2015, for example, Lebanon established restrictive border policies to stem the flow of Syrian refugees into the country (51). Intertemporal policy adjustment can counteract fluctuations in migration levels. As such, endogenizing policy in the simula-

tion could reveal a pattern of cyclical returns to equilibrium, in terms of volume and legal composition. A further question that future ABM research might seek to address is whether policy effects are asymmetric (52). For example, Is the magnitude of effect observed when transitioning from a more restrictive-policy scenario A to a more liberal-policy scenario B equivalent to the transition from scenario B to A, or does the size of the effect depend on the direction of the change? Finally, given the importance of network interactions for driving migrant adaptation (*SI Appendix*, section D.1), we encourage future scholars to use ABMs to examine additional functions of migrant networks.

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