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RESEARCH ARTICLE

Agent-based modeling for migration and modern slavery research: a systematic review

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Abstract

This systematic review aims to synthesize how agent-based modeling (ABM) has been used in migration and modern slavery research and provide the basis to model development for social science researchers exploring the use of ABM. We searched five bibliographic databases using two terminology categories: (1) migration or modern slavery terminology; (2) complex system methods terminology. Two reviewers conducted independent article screening. Peer-reviewed articles presenting original migration or modern slavery ABMs were included. Data extraction included model development steps and model characteristics. The dataset was synthesized and compared across studies. We identified 28 articles for inclusion. Many of the ABMs tested theories and about half were based on empirical data. Model development varied considerably and reported methods were extremely opaque. Only five studies used a structured development framework. The most common model involved agents deciding whether and where to migrate and attempting migration. Climate change was a common exogenous scenario modeled. Most of the ABMs did not undergo any sensitivity analysis or validation.ABM has a greater capacity to account for heterogeneous and dynamic decision-making than more frequently applied methods in research on migration and modern slavery. However, there is still a paucity of studies adopting ABM methods. These reviewed ABMs highlight gaps in the reporting and implementing of model development. ABM is a promising technique to address many urgent and complex questions in research on migration and modern slavery to better support decision-makers, but addressing current methodological gaps is a critical first step.

Keywords Agent-based modeling · Complex systems · Migration · Modern slavery · Trafficking

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Introduction

This review aims to explore how agent-based modeling (ABM), a complex systems science method, has been applied to research on migration or modern slavery, and to synthesize the ABM model development in this field of study to inform future applications of these methods. ABM, particularly in relation to socio-ecological systems modeling, has increasingly been employed to study many dynamic multi-scale research questions, such as ecosystem management, collective resource sharing and a particularly well-established method in studies of land use [1]. Ecological complex systems modeling has paved the way for bridging many other disciplines, including social sciences, with complexity science. We believe that interdisciplinary ABM methods present an opportunity to address many critical, unanswered, and complex questions in migration and modern slavery research and at the nexus of these two research topics. In a first step to advance the adoption of these methods in this field of research, this review synthesizes and assesses the use of ABM in migration and modern slavery research to date.

This review builds on the work of modelers that have been using and reviewing the use of ABM to explore emergent trends in migration, particularly migration influenced by environmental changes, social networks and decision processes, such as utility maximization [2–4]. Bell, Hernandez and Oppenheimer pointed out that many of the ABMs in this field focus on singular push-factors (e.g. climate change) and usually only consider the pull-factors or destination choices *after* the agents have surpassed a push-factor threshold [3]. Klabunde and Willekens explored the decision-model choices for migration ABMs that span several dimensions (forming expectations, evaluating options, the complexity of the decision, networks influencing decisions, etc.) and it is clear that not all of these dimensions are critically addressed or at least not articulated in current migration ABMs [2]. Many ABM modelers have asserted that without clear documentation of the full spectrum of model development (or 'modeling cycles', including final model validation), there are limitations to the contributions ABMs can claim or methodological advancements they can foster [1, 5]. In this vein, our aim is to contribute a systematic review of the model development of migration ABMs to allow for more informed dialogue on the gaps in model development and reporting of model development.

Why explore ABM for research on migration and modern slavery?

Many academics and practitioners are trying to understand the complexities of human migration to inform policy and practice, particularly to promote safer labor migration and address issues of modern slavery. For example, the United Nations' Sustainable Development Goals include taking "immediate and effective measures to eradicate forced labour, end modern slavery and human trafficking" (Goal 8.7) and to "facilitate orderly, safe, regular and responsible migration and mobility of people" (Goal 10.7) [6]. There is a growing body of research focusing on the causal pathways between low-wage labour migration and forms of labour exploitation, also known as modern slavery [7, 8]. Yet, there is limited evidence to explain the nexus

between low-wage labour migration and modern slavery completely [9], including evidence gaps on the complex mechanisms that contribute to entry into slavery-like conditions versus decent work [8, 10, 11]. That is, we have yet to understand the pathways that lead to different migration-related outcomes, in addition to understanding the drivers of migration as some of the previous ABM migration models have explored.

As an example, in public health, the disciplinary background of some of this reviews' authors, we have become increasingly aware that while the conventional epidemiological approaches can be useful to capture the effect of exposures on singular outcomes or offer estimates at the aggregate population-level data, they are often not suited to investigate the complex non-linear causal pathways that affect health (e.g. complex health behaviour problems) [12]. For example, epidemiological methods can describe well the aggregate experiences of migrant exploitation and health outcomes, such as the health outcomes of human trafficking [13], but they do not capture the complex system dynamics of labor migration and modern slavery. ABM has recently been recognized by the public health research community as a complex systems approach that can explore causal complexities inherent to human behavior and population health [14–16].

This paper gives a brief introduction to ABM of social systems and describes current applications of these methods for exploring complex systems in migration and modern slavery research. Finally, this paper presents findings to contribute methodological learning that is transferable across many social and health science disciplines.

Agent-based modeling for complex social systems

Agent-based modeling is a method for studying complex systems. A complex system contains many parts interacting at the individual (micro) level in an irregular way and generally producing non-linear outcomes with regularity at the systems, population or aggregate (macro) level [17–19]. Stephen Wolfram, one of the founding scholars on complex systems theory, said, "It is now a crucial problem for many areas of science to elucidate the mathematical mechanisms by which large numbers of such simple components, acting together, can produce behaviour of the great complexity observed" [20]. ABM is a computational simulation technique that has gained increasing popularity in recent decades across many social science disciplines to study social complexity in human systems [19]. For example, public health and health systems research has employed ABM methods to study communicable and non-communicable diseases, health behaviors, and other topics in social epidemiology [21]. These methods are increasingly recommended to evaluate complex health systems and prevention interventions [15, 22].

In simple terms, an ABM consists of a simulated population of autonomous, goal-oriented individuals (agents) that are capable of interacting with each other (agent-to-agent) or with their simulated environment (agent-to-environment). Agents can be assigned specific attributes (demographics, attitudes, risk aversion, etc.) that in combination with the rules of the model (how individuals behave, make decisions,

interact with their surrounding environment, etc.) govern the steps that result in the dynamic and emergent outcomes [23].

Experts from both computer science and social science have written extensively on the unique capabilities and usefulness of ABMs in social science research [17, 19, 24, 25]. In short, ABMs have a bottom-up approach that enables exploration of individual-level behaviors and causal mechanisms that lead to macro-level aggregate emergent phenomena, which can only be inferred from modeling the individual-level interactions. The task is to replicate a population, the environment and its patterns in such a way that the model produces similar emergent properties or outcomes to the observed outcomes in the real world [26]. Some scholars in this methodological field argue that the next frontier of explanatory social science research is being able to 'grow' the phenomenon of interest from micro-level rules [17]. For example, recent ABM research on health-pertinent behaviors, such as smoking, diet and interpersonal violence, has successfully simulated groups of individuals that move in a social or physical space, exchange information, model behavior, copy behavior and make decisions [21, 27]. All of these individual actions in aggregate replicate real-world trends in health behaviours and outcomes, such as smoking habits or obesity, amongst close ties in social networks.

An example of a complex dynamic system in migration research: Low-wage labour migration and exploitation

Globally, the majority of migrants participate in the labor force [11]. The majority of victims of modern slavery are low- or no-wage laborers and a significant proportion are migrant workers [10]. These two global phenomena, low-wage labor migration and modern slavery, are linked in complex and dynamic ways. Figure 1 is a conceptual framework visualisation depicting some of this complexity. In Fig. 1, we present the migrant on a pathway between origin and destination and, in some cases, a pathway that returns to origin. Individuals very rarely migrate without the help of social or intermediary networks, such as migrant networks at destination or labor recruitment networks [28]. Thus, we have also presented the migrant connected to a

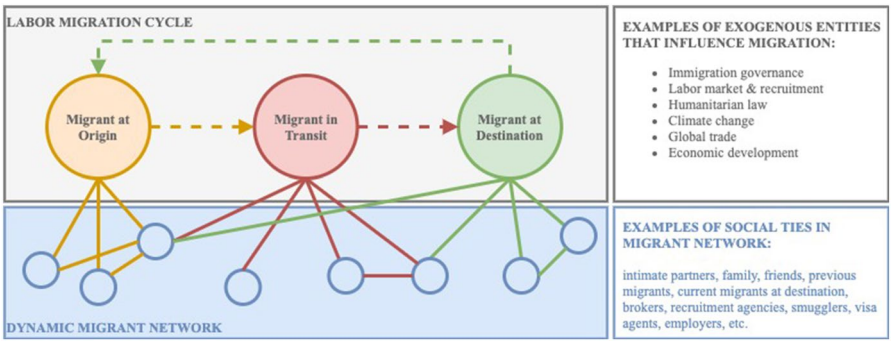

Fig. 1 Framing low-wage labor migration as a complex dynamic system across multiple geographic spaces: Agents, networks and exogenous influencers

dynamic network of possible relations that evolves throughout the migration cycle. These migration–facilitation networks and any associated social or migratory norms are also influenced by exogenous entities, such as climate change, economic development and labor recruitment [29]. An individual experience of migration is influenced by all of these factors (for example, individual behaviors, social networks, social norms, immigration governance or labour markets). Not included in Fig. 1 are the range of outcomes at every stage in the migration cycle on individual and population levels that operate through feedback mechanisms which, over time, cause emergence of population-level migration behaviour which can only be inferred from individual-level interactions.

Theoretical developments in the fields of migration research and public health research draw attention to the multi-causal, dynamic, multi-directional and non-linear nature of complex social problems, including the ecological systems approach to addressing social phenomena and the importance of concepts of social networks, decision-making under uncertainty and bounded rationality [2, 9, 16, 27, 30, 31]. There is a convincing argument for adopting new methods of data collection and analysis that reflect these theoretical concepts. Agent-based modeling enables complex dynamic system simulation that encompasses multiple ecological levels (individuals, households, social networks, migration corridors) and incorporates heterogeneous individual decision-making and behaviors (such as the system in Fig. 1).

Donors, practitioners and policymakers advocating for the protection and well-being of low-wage labor migrant workers rely on research to provide evidence on the challenges these individuals face during their migration and employment, to inform effective interventions. To date, a majority of this research has been conducted using conventional statistical or qualitative research methods. The statistical methods implicitly treat labor migration as a one-dimensional, one-directional, linear and static "exposure–response"-type relationship between drivers of migration and migration outcomes. Such methods do not take into consideration the complexity of labor migration or its dynamic nature. These analyses do not account for the various feedback mechanisms governing the interaction of different actors with other actors and with their environment, the time delays between a stimulus (action) and the corresponding response, and the non-linear nature of responses to stimuli. The current body of evidence primarily tries to offer insights into the drivers of migration, the demographics of migration, migration corridors and outcomes, including growing evidence on the range of harmful outcomes, such as unfair recruitment, labor exploitation and forms of modern slavery. But, these analyses do not improve our knowledge on labour migration processes or the nature of the complex exposures and mechanisms related to migration. Every story of migration encompasses information-seeking, decision-making, interactions and exchanges with individuals, groups and systems.

Examples of other ABM reviews

As referenced earlier, to our knowledge, there are three reviews of migration ABMs relevant to the aim of this review, including Klabunde and Willeken's review focusing

on decision-model choice including integration of social networks ($n=22$ included publications) [2], Thober and colleagues' review of ABMs of environmental-migration linkages ($n=21$) [4], and Bell and colleagues' brief background review on ABMs exploring migration push–pull factors to present their migration ABM framework (non-systematic, $n=\sim 8$) [3]. Other examples of ABM reviews include previous reviews on the use of ABM to study other social or health science topics, such as urban crime ($n=45$) [32], non-communicable diseases (NCDs) ($n=22$) [33], obesity ($n=38$) [34], public health (non-systematic, $n=\sim 45$) [21], and health systems ($n=11$) [35]. These reviews reported notable increased interest in and application of ABM methods in their respective field of study, despite still small yields compared to other reviews including different methods. The reviews focused on urban crime, NCDs, obesity, and public health all discussed the current gaps in standardised ABM methods and a lack of transparency in model development as a major limitation in the field for model replication and systematic comparison. Cassidy et. al.'s review on the use of ABM and System Dynamics (SD) models in healthcare systems research did not conduct extensive extraction on model development processes, and so did not address these issues, but did conclude that the topic of data source choices is a critical next area of review in complex healthcare systems modeling [35]. The most relevant of all these reviews to the present one is Klabunde and Willekens's review of ABMs of migration, which differs from this review as it focused primarily on the behavioural theories that informed the decision-making models [2]. The present review draws on this previous work and proposes a wider scope of investigation. The key contribution of this review is to incorporate a broader set of search terms to include modern slavery phenomena as well as migration. Furthermore, this review extracted data points on the full spectrum of the ABM development process, not just the decision-making element. We will reference Klabunde and Willekens's review throughout the methods and discussion sections of this paper, particularly because of the strength of that review's synthesis and analysis of the decision-making process which was not within the scope of this review, but an important topic for ABM development.

Review aim

This review aims to describe how ABM has been used in research on migration and/or forms of modern slavery. Findings are intended to inform future studies on the application of this methodological approach, including guidance on model calibration, model development, sensitivity analysis, and model validation. This review aims to contribute a summary and assessment of the state of the art of ABM used in migration and modern slavery studies to encourage and inform future adoption of ABM methods in this field.

Methods

This review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement [36]. The full protocol for this review, including comprehensive database search scripts, can be shared upon request to the corresponding author. A condensed version of the search protocol can be found in the Supplementary Materials (SM-1). The summary of the methodology is outlined here.

Sources

The search was conducted on 5 bibliographic databases covering public health, social science, and computer science disciplines (See Table 1 for details).

Search strategy

The search strategy included two subject areas: (1) migration or modern slavery; and (2) computational dynamic systems modeling or network analysis methods. We developed a conceptual framework that depicts the review concepts (See Fig. 2) to guide our terminology inclusion in the search scripts (See Table 2). The search scripts are included in the Supplementary Material (SM-1).

Eligibility criteria

The search only included peer-reviewed articles published between 1 January 1999 and the date of search (See Table 1). Additionally, the full article had to be available in English. We did not apply any exclusion criteria based on the discipline, data sources (quantitative, qualitative, secondary, theoretical, etc.), study type (cross-sectional, longitudinal, trial, etc.), quality of the study, or the publishing journal. The studies needed to meet two criteria pertaining to (1) the study topic and (2) the study methodology.

1. Study topic

   The research questions and outcomes of the study addressed one or more of the following themes: migration flows; drivers of migration; demographics of migrant populations; migrant social networks during migration planning, implementation or job-seeking; migrant labor; immigration policy; labor recruitment; safer labor

Table 1 Bibliographic database searches

Databases	Date of search	Filters applied
Web of Science, Scopus, PubMed	09/06/2019	Document type: Articles; Reviews Years: 1999–2019
MathSci, arXiv	18/09/2019	

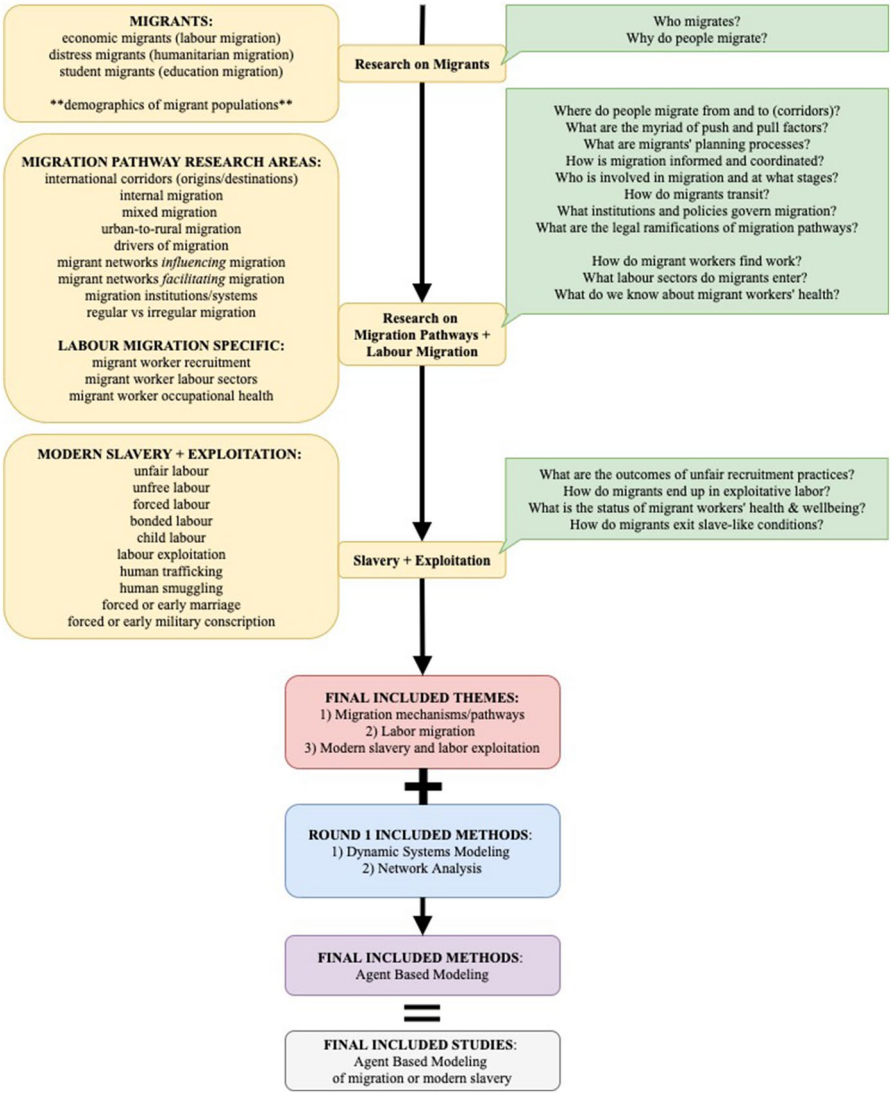

Fig. 2 Conceptual framework of key concepts applied for the review's search

migration interventions or migrant worker health interventions; remittance flow; return migration; modern slavery or child labor (including child soldiers).

The search protocol outlined similar topics that would *not* be included: disease spread through migration; general migrant population health at destination (unless specific to migrant workers or forms of modern slavery); humanitarian coordination or service delivery broadly; disaster preparedness or short-term emergency evacuation; residential or local migration (for example, urban sprawl, residential neighborhood choice, etc.); ethnic diversity at destination (without exploring

Table 2 Summary of the two-concept search strategy with 'not' search terms

Concept 1: migration; low-wage or hazardous labor; labor recruitment; modern slavery or human smuggling	Concept 2: complex system simulations; network analysis
1: Migration1: Migration migrat* OR migrant* immigrat* OR immigrant* emigrat* OR emigrant* refugee* assylum "internal* displace*" (displace* NEAR/4 people*) (displace* NEAR/4 population*) humanitarian **2: Low-wage or hazardous labour "low-wage"** "low-skill" (occupation* NEAR/4 (health OR safety)) "trade union*" **3: Labor recruitment** labo$r recruit* labo$r broker* lab$or agent labo$r intermediar* "labo$r market*" "labo$r supply"	**4: Modern slavery** (human NEAR/4 traffick*) (human NEAR/4 smuggl*) (migrant* NEAR/4 traffick*) (migrant* NEAR/4 smuggl*) (refugee NEAR/4 traffick*) (refugee NEAR/4 smuggl*) "modern slave*" "forced labo$r*" "forced work*" "child labo$r*" "child work*" (child NEAR/4 traffick*) "bonded labo$r*" "bonded work*" "debt bond*" "unfree labo$r" "labo$r NEAR/4 (exploit* OR abus*)" "early marriage*" "child marriage*" "child bride*" "forced marriage*" "forced bride*" (bride NEAR/4 traffick*) "forced conscription" "child soldier*" "rebel wives"	**1: Dynamic system modeling** "agent-based model*" "individual-based model*" "stochastic-dynamic model*" "computational agent*" "cellular-automata*" "social simulat*" microsimulat* ("machine learning" NEAR/4 "dynamic system*") (system* NEAR/4 "interact* object*") "system dynamics" "complex system* simulation" "complex system* model*" "discrete-event simulation" "discrete-time Markov chains" **2: Network analysis** "network analysis" "network data" "network model*" "bayesian network"

NOT: (cancer* OR tumo$r* OR protein* OR gene OR genetic OR genomic* OR oncolog* OR immunolog* OR "earth-system* model*" OR "oceanic-migration*" OR "bird NEAR/4 migrat*" OR "fish-migration" OR species OR "cell-migrat*" OR breed* OR molecul* OR bacteria* OR particle* OR "cell–cell" OR tissue OR larva* OR ecosystem* OR egg* OR predator* OR sedement*)

migration mechanisms or networks that facilitated migration); immigrant cultural integration at destination (except where relevant to employment or earnings as described above); animal migration; tourism; or broad low-wage or hazardous occupation research without disaggregation by migrant status.

2. Study methodology

   The search had two-stage inclusion criteria. The first stage included a broader range of computational dynamic systems and network methodologies that could provide more comprehensive findings on the types of innovative methodologies being used in migration studies. This stage also was designed to prepare for a paucity of literature on ABMs to review in this subject area. The second-stage inclusion criteria, which was applied to the articles that were eventually fully extracted for this review, included only original research that used ABM. The results described in this paper are based on the articles identified using the second-stage criteria.

Study selection

The full database yields were uploaded to the Rayyan systematic review software and de-duplicated [37]. Two co-authors completed independent-blind abstract reviews for the 1707 articles. The reviewers met in person to discuss a collection of 100 articles that received conflicting decisions (one reviewer included and one reviewer excluded). The two reviewers were able to agree on inclusion or exclusion for all 100 articles through referral to the study protocol and without the need for a third reviewer. In total, 137 articles were included after the first round of abstract screening. Then a second round of abstract screening was completed to narrow the yield to agent-based models only and to be full-text screened. At the final screening stage, 58 articles were full-text screened, and of these, 28 articles met the final inclusion criteria. For more details on the screening process and reasons for exclusion, see Fig. 3.

Data extraction

This is a review of the *methodology* of these studies, not a synthesis of findings. Therefore, the data extraction process captured the authors' affiliations and study aim, model inputs, model development, model process and the analysis and validation methods completed by the authors. This method is similar to systematic reviews of ABMs on other social or health science research topics that focused on the study design, model specifications (agents, environment, decision rules), and model analysis (sensitivity analysis, model validation) for data extraction and synthesis [33, 34, 38–41]. The data extraction tool was informed by the guiding questions outlined in the Overview, Design Concepts and Details + Decision-Making (ODD + D) protocol for ABM development, which is an adaptation of the original Overview, Design

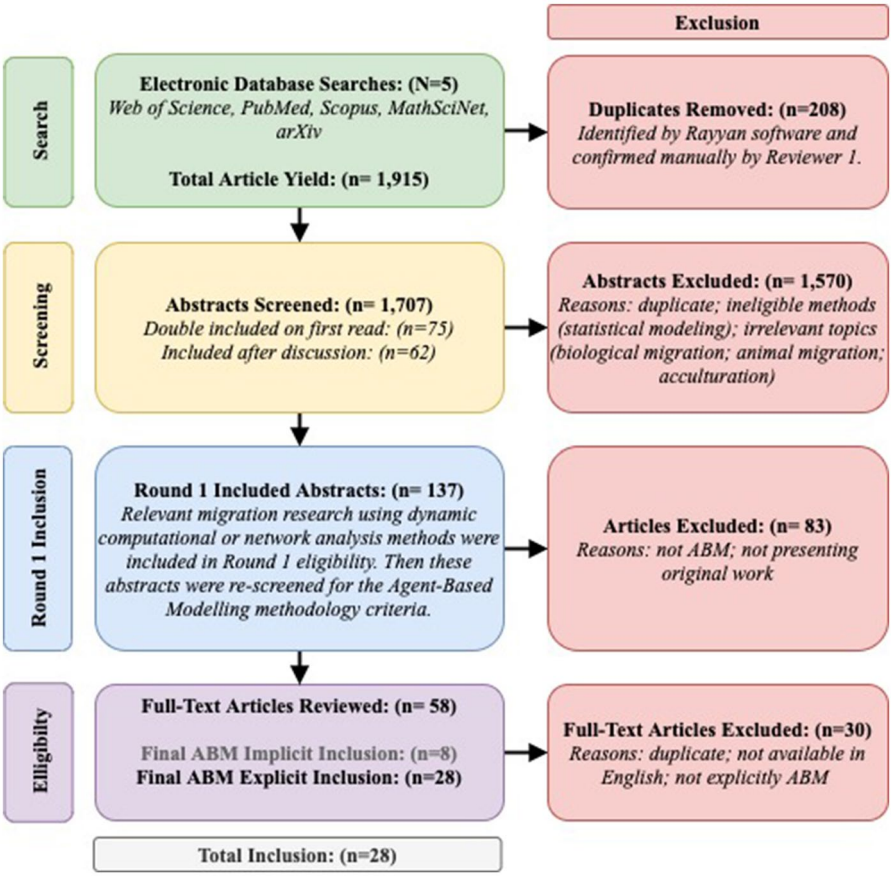

Fig. 3 PRISMA systematic review flowchart

Concepts and Details (ODD) protocol developed to standardize descriptions of individual-based models (IBMs) and ABMs [5, 42, 43]. Before the development of the ODD framework in 2006, computer-simulation models, such as ABMs, did not have standardised guidelines for dissemination [42]. Therefore, without these protocols, IBMs and ABMs were reported with varying levels of detail and often in insufficient detail to understand all of the modeling choices. The ODD framework elicits critical descriptives of the model design and development and the ODD + D protocol added detailed guidance on how to report the decision-making elements in the development framework, which was particularly important for ABMs. We believe that the ODD + D framework offers a valuable approach to extracting and understanding model development and model comparison across studies and encouraging wider use of this framework by other ABM modelers, particularly in the social sciences.

The lead author for this review extracted the data points from all 28 articles using comma-separated value (CSV) files according to key questions in the ODD + D protocol. The extraction table was quality-checked by all three co-authors in both workshop-style review sessions and independent reviews.

Data synthesis

Since the majority of the data points extracted for this review were descriptive characteristics of the ABMs, the data extraction table is largely qualitative and too large to present in article format. In this same respect, the challenge to qualitative data synthesis in systematic reviews also applies to this methodological

Table 3 Results synthesized by sub-topic and presented in individual tables

All tables	Lead author (Year)
Table 4: Included articles	Author(s)
	Year
	Title
Table 5: Study characteristics	Authors' institutional affiliation(s) (country)
	Authors' department(s)
	Journal
	Study purpose as summarised by reviewers (aim sub-category classification)
Table 6: Model inputs	Decision model
	General concepts or theoretical basis for model design
	Data type
	Data source
Table 7: Model development	Time-steps and time-horizon
	Spatial characteristics
	Agent types: Agent attributes [micro characteristics]
	Exogenous or environmental characteristics [macro characteristics]
	Social networks [meso characteristics]
Table 8: Model process	Initialisation
	Model steps and decision rules
	Agent types: Agent actions
	Simulation scenarios
	Deterministic or stochastic (if stochastic: which model component)
Table 9: Model analysis and validation	Output variables
	Uncertainty and sensitivity analysis as described by the author(s)
	Model validation as described by the author(s)
Table 10: Summary of model aim and model development	

Table 4 Included articles

Author(s)	Year	Title
Alghais N, Pullar D, Charles-Edward E [46]	2018	Accounting for peoples' preferences in establishing new cities: A spatial model of population migration in Kuwait
Anderson J, Chaturvedi A, Cibulskis M [47]	2007	Simulation tools for developing policies for complex systems: Modeling the health and safety of refugee communities
Cai N, Ma HY, Khan MJ [48]	2015	Agent-based model for rural–urban migration: a dynamic consideration
Chesney T, Evans K, Gold S, Trautrims A [49]	2019	Understanding labour exploitation in the Spanish agricultural sector using an agent based approach
Entwisle B, Williams N, Verdery A, Rindfuss R, Walsh S, Malanson G, Mucha PJ, Frizelle BG, McDaniel PM, Yao XZ, Heumann BW, Prasartkul P, Sawangdee Y, Jampaklay A [50]	2016	Climate shocks and migration: an agent-based modeling approach
Espindola AL, Silveira JJ, Penna TJP [51]	2006	A Harris-Todaro agent-based model to rural–urban migration
Fu Z, Hao L [52]	2018	Agent-based modeling of China's rural–urban migration and social network structure
Garcia- Diaz C, Moreno-Monroy A [53]	2012	Social influence, agent heterogeneity and the emergence of the urban informal sector
Hailegiorgis A, Crooks A, Cioffi-Revilla C [54]	2018	An agent-based model of rural households' adaptation to climate change
Hassani- Mahmooei B, Parris BW [55]	2012	Climate change and internal migration patterns in Bangladesh: An agent-based model
Henry A, Christensen A, Hofmann R, Steimanis I, Vollan B [56]	2017	Influence of sea level rise on discounting, resource use and migration in small-island communities: An agent-based modeling approach
Ichinose G, Saito M, Sayama H, Wilson DS [57]	2013	Adaptive long-range migration promotes cooperation under tempting conditions
Janssen MA [58]	2010	Population aggregation in ancient arid environments
Kniveton D, Smith C, Wood S [59]	2011	Agent-based model simulations of future changes in migration flows for Burkina Faso
Kniveton D, Smith C, Black R [60]	2012	Emerging migration flows in a changing climate in dryland Africa
Mena C, Walsh S, Frizzelle B, Xiaozheng Y, Malanson G [61]	2011	Land use change on household farms in the Ecuadorian Amazon: Design and implementation of an agent-based model
Naivinit W, Le Page C, Trebuil G, Gajaseni N [62]	2010	Participatory agent-based modeling and simulation of rice production and labor migrations in Northeast Thailand
Naqvi A, Rehm M [63]	2014	A multi-agent model of a low income economy: simulating the distributional effects of natural disasters
Naqvi A [64]	2017	Deep Impact: Geo-Simulations as a Policy Toolkit for Natural Disasters

Table 4 (continued)

Author(s)	Year	Title
Raczynski S [65]	2018	Influence of the gregarious instinct and individuals' behavior patterns on macro migrations: Simulation experiments
Silveira JJ, Espindola AL, Penna TJP [66]	2006	Agent-based model to rural–urban migration analysis
Simon M [67]	2019	Path Dependency and Adaptation: The Effects of Policy on Migration Systems
Smith C [68]	2014	Modeling migration futures: Development and testing of the Rainfalls Agent-Based Migration Model—Tanzania
Suleimenova D, Bell D, Groen D [69]	2017	A generalized simulation development approach for predicting refugee destinations
Tabata M, Eshima N (1 of 2)[1] [70]	2003	A self-referential agent-based model that consists of a large number of agents moving stochastically in a discrete bounded domain
Tabata M, Eshima N (2 of 2)[1] [71]	2004	The behavior of stochastic agent-based models when the number of agents and the time variable tend to infinity
Walsh S, Malanson GP, Entwisle B, Rindfuss RR, Mucha PJ, Heumann BW, McDaniel PM, Frizelle BG, Verdery AM, Williams NE, Yao XZ, Ding D [72]	2013	Design of an agent-based model to examine population-environment interactions in Nang Rong District, Thailand
Wu J, Mohamed R, Wang Z [73]	2011	Agent-based simulation of the spatial evolution of the historical population in China

[1]Due to the significant similarities between Tabata's [70, 71] model presentations, these articles have been extracted together in one row of the data extraction Tables (5, 6, 7, 8, 9, 10)

review [44]. When possible, we have categorized certain data extraction points to more easily summarize or draw conclusions on the range of methodological choices made by the authors. Therefore, we have grouped a majority of the data extraction into seven results Tables (4, 5, 6, 7 8, 9 and 10) and presented our data synthesis for each table (See Table 3 for summary of results tables). The synthesis includes categorizing and summarizing the key data extraction points to make comparisons and highlight gaps across all 28 ABMs. The full data extraction table can be found in the Supplementary Materials (SM-3). We did not assess the quality and suitability of ABM methods used in the included studies because it is outside the scope of the review. This is in part because, to our knowledge, there is not currently a standardised instrument to assess the quality of ABM models like the tools that exist for assessing other research methods, such as The Critical Appraisal Skills Program (CASP) tool [45].

Results

In total, we identified 137 articles on relevant migration or modern slavery research topics that applied either network analysis or dynamic simulation methods. This included research using social network analysis, Bayesian network analysis, system dynamics modeling and various microsimulation methods. We then further excluded any article that did not use ABM methods. We identified 28 articles, included in this review, which explicitly detailed ABM (or 'Agent Based Simulation') in the methods (Table 4).

This results section presents: the data extraction and synthesis of the study characteristics (Table 5); model inputs (Table 6); model development (Table 7); and model process (Table 8); model analysis (Table 9); and the summary of the model aim in relation to specific model development characteristics from Tables 5, 6, 7, 8, 9, 10. But first, we will present two important observations made during the screening and extraction process that are relevant to inferences about methodological procedures in ABM, one of the key objectives of this review:

(1) Agent-based models are sometimes called by different names;

(2) Few studies reported using ODD + D or an alternative development framework.

1. Agent-based models are sometimes called by different names

   Similar to findings from Klabunde's and Willeken's review, it was challenging to ascertain whether some dynamic simulation models (e.g. spatial or dynamic microsimulations, individual-based models) that were not explicitly called ABM (or ABS) did in fact include sufficient agent-interaction or decision-based behavioral modeling to be included as ABMs [2]. This challenging grey area of inclusion is not altogether surprising, since expert commentaries on the origins of ABM explain that cellular automata, microsimulations, and agent-based approaches have been developed and improved on in parallel, across disciplines, with different aims, and different names, but seemingly similar function and capabilities [74, 75]. For example, microsimulations are often considered to be

the method of choice when exploring policy impacts and ABM are used more commonly for theory testing. Distinctions aside, these models all have bottom-up approaches that model individual behaviors, often heterogeneous [75]. While at times the distinction appears arbitrary, for this systematic review, we decided to apply strict criteria that the paper had to identify the methods as ABM to be included in the extracted yield of articles. In part, this is to ensure the reproducibility of the review, but also to allow for as uniform and complete data extraction of methodological processes as possible, which we determined would be more feasible if the authors were writing their methods from an ABM framework. We have included a table in the Supplementary Materials (SM-2) with a list of the 8 articles we determined were implicitly describing ABM but were excluded for the reason just described.

2. Few studies reported using ODD + D or an alternative development framework

   Although the majority ($n = 24$) of the included articles were published after the introduction of the well-known 2006 ODD framework for simulation or the 2013 ODD + D framework for ABMs (See Table 4 for publication years), very few of the articles described using any framework in developing or reporting the ABM. Only one study used the ODD + D framework designed specifically with ABMs in mind [54], 3 studies used the ODD framework [46, 55, 62], and one used a framework developed by the authors themselves which they called a generalized Simulation Development Approach (SDA) [69]. This review, as noted, used the ODD + D framework to inform the data extraction tool, in part, because we hoped a majority of recent ABM research would have used this framework. It appears that the uptake of this framework tool is still slow and this continues to create challenges for understanding model inputs, development and analysis as well as comparison across studies. We note this before addressing the bulk of the synthesis of the study methods to inform the reader that the extraction process had to adapt to a wide range of styles in disseminating the model development process.

Below are the main results of this review according to the six sections described above in Table 3.

1. Study characteristics

   Between 1999 and 2019, the publishing years of inclusion in this review, there have been a steadily increasing number of studies using agent-based modeling to investigate the migration and modern slavery topics covered by this review (See Fig. 4).

   The authorship characteristics, both by institutional affiliation and by disciplinary associations, represented a diverse range of home institutions, country of institutions and disciplinary departments or research centers (See Table 5). Nine of the included studies were authored by multi-country authorship teams and

Table 5 Study characteristics: Authors' institutional affiliations and disciplines, journal of publication, and summarised study purpose

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Alghais [46]	The university of queensland (Australia)	Environmental science	Plos One	To explore segregation levels, internal migration and residence preferences in Kuwait urban areas	Migration demographic or regional
Anderson [47]	Purdue university (USA)	Sociology, Anthropology	Health care management science	To understand the collective behaviors of refugees and internally displaced persons	Humanitarian migration
Cai [48]	Northwest University for Nationalities (China), National University of Sciences and Technology (Pakistan)	Engineering, Economics	Physica A: Statistical Mechanics and its Applications	To simulate rural–urban migration	Migration demographic or regional
Chesney [49]	Nottingham University (UK), University of Kassel (Germany)	Business, Economics	Journal of Cleaner Production	To explore the diffusion of slavery and anti-slavery practices in the agricultural industry	Slavery
Entwisle [50]	University of North Carolina at Chapel Hill (USA), University of Washington (USA), East–West Center (USA), University of Iowa (USA), Center for Geographic Information Science (USA), Mahidol University (Thailand)	Demography, International Studies, Sociology, Geography, Mathematics,	Population and Environment	To examine how climate shocks affect migration in rural agricultural areas of Thailand	Environmental motivations for migration

Table 5 (continued)

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Espındola [51]	Universidade Federal Fluminense (Brazil), Universidade Estadual Paulista (Brazil)	Physics, Economics	Brazilian Journal of Physics	To explore crucial assumptions of an economic utility maximisation migration model	Migration theory testing
Fu [52]	Johns Hopkins University (USA)	Civil Engineering, Sociology	Physica A: Statistical Mechanics and its Applications	To understand the co-evolution of social networks and China's rural–urban migration patterns	Social impacts on migration
Garcia- Diaz [53]	University of Antwerp (Belgium), Universidad de los Andes (Colombia), University of Groningen (The Netherlands)	Management, Industrial Engineering, Economics	Physica A: Statistical Mechanics and its Applications	To explore the informal labor sector and social influences in urban–rural migration	Social impacts on migration
Hailegiorgis [54]	George Mason University (USA)	Social Complexity	Journal of Artificial Societies and Social Simulation	To explore the adaptive capacity of Ethiopian rural households with respect to climate and land-use variations	Environmental motivations for migration
Hassani- Mahmooei [55]	Monash University (Australia)	Econometrics	Environment and Development Economics	To study the population migration dynamics in Bangladesh due to extreme environmental shocks	Environmental motivations for migration

Table 5 (continued)

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Henry [56]	University of Arizona (USA), University of Copenhagen (Denmark), Ludwigs-Maximilians-Universität München (Germany), Philipps-Universität Marburg (Germany)	Public Policy, Geosciences, Economics	Environmental Conservation	To illustrate the importance of resource payoffs on individuals' migration in Pacific and Caribbean islands	Economic utility of migration
Ichinose [57]	Anan National College of Technology (Japan), State University of New York (USA)	Complex Systems, Biology, Anthropology	Scientific Reports	To study the interaction between co-evolutionary cooperation and migration	Social impacts on migration
Janssen [58]	Arizona State University (USA)	Human Evolution and Social Change	Ecology, Society	To explore the resilience, decision making and movement of the population in response to climate variability and resource degradation	Environmental motivations for migration
Kniveton [59]	University of Sussex (UK)	Geography, Informatics	Global Environmental Change- Human and Policy Dimensions	To investigate the role of the environment in Burkina Faso in indivduals' decision to migrate	Environmental motivations for migration
Kniveton [60]	University of Sussex (UK)	Geography	Nature Climate Change	To explore how climate and demographic changes influence migration within and to Burkina Faso	Environmental motivations for migration

Table 5 (continued)

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Mena [61]	Universidad San Francisco de Quito (Ecuador), University of North Carolina at Chapel Hill (USA), University of Iowa (USA)	Environmental Sciences, Geography, Demography	Applied Geography	To assess the drivers of land-use change and migration as an adaptive response in the Ecuadorian Amazon	Environmental motivations for migration
Naivinit [62]	Chulalongkorn University (Thailand), Université Paris Ouest Nanterre-La Défense (France), Ubon Rajathanee University (Thailand)	Unspecified, Biology	Environmental Modelling & Software	To build a representation of rainfed lowland rice farming, water availability, and labor migration in Thailand	Environmental motivations for migration
Naqvi [63]	Vienna University of Economics and Business (Austria), Chamber of Labor (Austria)	Economics, Labor	Journal of Economic Interaction and Coordination	To capture adjustments and spatial spillover effects following disaster-like negative shocks in Pakistan	Humanitarian migration
Naqvi [64]	International Institute for Applied Systems Analysis (Austria), Vienna University of Economics and Business (Austria)	Applied Systems Analysis, Ecological Economics	World Development	To create a geo-simulation that replicates natural disaster outcomes to identify vulnerability hotspots for relief delivery	Humanitarian migration
Raczynski [65]	Universidad Panamericana (México)	Engineering	Journal of Human Behavior in the Social Environment	To simulate the migrations of social groups influenced by the gregarious effect and individual behavior patterns	Social impacts on migration

Table 5 (continued)

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Silveira [66]	Universidade Estadual Paulista (Brazil), Universidade Federal Fluminense (Brazil)	Economics, Physics	Physica A: Statistical Mechanics and its Applications	To examine rural–urban migration during the industrialization process	Migration demographic or regional
Simon [67]	University College London (UK)	Political Science	Journal of Artificial Societies and Social Simulation	To demonstrate how migrants adapt to policy change by showing the effect of return migration flows	Migration demographic or regional
Smith [68]	University of Sussex (UK)	Geography	Climate and Development	To explore the role of rainfall in shaping the drivers of migration within the Tanzanian communities surveyed	Environmental motivations for migration
Suleimenova [69]	Brunel University London (UK), University College London (UK)	Computer Science	Scientific Reports	To predict the distribution of refugees across camps in three African conflicts to inform governments and organisations responding in humanitarian crises	Humanitarian migration
Tabata* [70, 71]	Kobe University (Kobe, Japan), Oita Medical University (Oita, Japan)	Applied Mathematics, Statistics	Applied Mathematics and Computation	To describe interregional migration theory	Migration theory testing

Table 5 (continued)

First author (Year)	Author institutional affiliations (country)	Author department disciplines	Journal	Study purpose (summarised)	Broad research category
Walsh [72]	University of North Carolina at Chapel Hill (USA), University of Iowa (USA), Central Michigan University (USA), University of Washington (USA)	Geography, Demography, Sociology, Mathematics, Information Science, Spatial Analysis, International Studies	Applied Geography	To examine land use change in agricultural Thailand and migration as an adaptive response	Environmental motivations for migration
Wu [73]	Chinese Academy of Sciences (China), Wayne State University (USA), East China Normal University (China), University of Science and Technology of China (China)	Policy, Management, Geography, Urban Planning	Journal of Historical Geography	To simulate the spatial evolution of the population of China over the past 2000 years	Migration demographic or regional

The models presented in Tabata's paper [70, 71] are identical by most of the points extracted for this review

thirteen of the included articles indicated cross-disciplinary authorship teams. It is also noteworthy that ten of those cross-disciplinary authorship teams consist of both "hard sciences" (mathematics, engineering, physics, etc.) and "soft sciences" (sociology, anthropology, economics, demography, etc.). For example, the Walsh et al. article was authored by scholars from backgrounds in mathematics, information science, spatial analysis, geography, demography, sociology, and international studies, who could each bring his or her disciplinary expertise to the task of mathematically modeling environmentally influenced migration patterns [72].

For each study, the aim defines how to calibrate the model (choosing the data sources and applying various data sources to different elements of the model) and how to develop the model (the time, space, agents and environment, as well as the model decision rules). The included studies present a range of exploratory aims, which we have grouped into seven broad sub-categories: migration demographic or regional trends; environmental motivations for migration; migration theory testing; humanitarian migration trends; the social influence on migration patterns; the individual economic utility of migration; and slavery. The two most frequent research categories were: exploring the environmental motivations for migration, such as climate change, environmental shocks or land-use changes ($n=10$); and explorations of migration corridor trends by geography or demographics ($n=5$). The other study aims fell into the following categories: humanitarian migration trends ($n=4$); social influences on migration patterns ($n=4$); migration theory testing ($n=3$); individual decision-making based on the economic utility of migration ($n=1$); and the diffusion of slavery ($n=1$). None of the studies explicitly aimed to understand various migration pathways and individual processes of migration, since most were focused on macro-drivers of migration trends, such as expected wage differentials, weather conditions or humanitarian situations.

2. Model inputs

Most studies used multiple types of data (theory, primary, secondary, historical, cited research, reports, etc.) to calibrate the model parameters, initial settings, environmental characteristics, scenarios or decision rules (See Table 6). Recently, the computational social science community has begun to devote more attention to empirical calibration and validation of ABMs [76], where previously the vast majority of ABMs have been calibrated solely as thought experiments using theory. In this review, 5 articles reported using primary empirical data for ABM calibration and 11 studies used secondary data sources (excluding GIS data, historical climate data, or cited research findings as 'secondary data'), an approach that some have called an 'indirect strategy' for empirical calibration that is a limited but promising option when collecting primary empirical data is not feasible. The notable difference between the studies that used primary versus secondary empirical data is that all 5 studies that collected primary data used the analysis of this data to inform individual behavioural rules in the model (e.g. how migrants decide to migrate) but only 5 (of 11) of the studies that only used secondary data sources did so to inform individual behavioural rules. Both primary and secondary empirical data sources were used to inform agent attributes ($n=2$), population size and attributes ($n=4$), population trends (e.g. migration flows, household crop yields, household spending) ($n=5$), social networks ($n=1$),

regional land use ($n=3$) and key events (e.g. natural disasters, conflicts) ($n=2$). The use of empirical and secondary data sources in this review reflects the wider trends in empirically calibrated ABMs, which is usually more common to find secondary data that can inform the model structure components (types of agents, number of agents, environmental characteristics) but less common to find secondary data sources that offer the rich data on behaviors and interactions that are often so central to the theoretical research questions [76].

Most commonly ($n=21$), the ABM decision rules or assumptions were informed by theory, primarily from economics, psychology or theoretical developments in the field of migration studies. In fact, 9 of the ABMs exclusively used theories to calibrate the models, such as theories on the push and pull factors of migration or the influence of social networks on migration, to calibrate the model, as can be reviewed in Table 6. This is not surprising given the scarcity of migration data collected from a complex systems approach that would be easily translatable to ABMs. For example, ABMs modeling labor migration as a complex system would need data on migrants' social networks' role in the migration process, the interactions between migrants and the wider systems environment, or the decision-making process of migrants, labor intermediaries and employers. There is a high burden to collecting this kind of data in any setting, and there are additional challenges in research with a largely hidden and mobile population, such as low-wage international migrant workers or human trafficking victims [77, 78]. Boero and Squazzoni point out that despite the challenges to missing, incomplete or scarce data in many fields of research, the valuable theoretical constructs produced using ABM methods need to be embedded in empirical findings (at both calibration and validation stages of model development) so that the theoretical mechanisms are empirically grounded in the real-world phenomena [76].

Studies that employed secondary datasets ($n=15$) sourced the datasets from various federal and municipal governmental departments, as well as national and international non-government organisations, such as the World Bank or United Nations [47, 59, 60, 63, 64, 69]. For spatial calibration of the model, eight ABMs used some type of GIS data. Only one study used participatory methods in calibrating the model with key stakeholders by hosting ABM workshops at various stages in the model development [62]. Additional data sources included in-depth case studies, secondary research findings in the literature, non-peer-reviewed reports and historical trends in weather or migration (See Table 6). The models pulled from a wide range of theoretical knowledge and empirical analysis to inform model development and decision-model choices. For example, the range of theory and background analysis included psychology-based theories of well-being and decision-making, information diffusion, cooperation theory, systems theory, social network theory, topics in microeconomics, game theory and a range of topics pertaining to migration push–pull factors (See Table 6).

The model's data inputs often determine the decision model used in an ABM. An ABM can employ more than one decision model, such as a combination of simple heuristics (breaking down agent actions into simpler if/then rules) and decision theory (generalized knowledge on human's reasoning and process in making decisions) or microeconomics utility maximisation (the aim is maximis-

Table 6 Model inputs: Data types, data sources, and theoretical basis or relevant background themes

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Alghais [46]	Primary empirical, GIS, reports, secondary	(1) Residential survey data sent via social-media (2) Kuwait Institute for Scientific Research population data (3) Kuwait Finance House Real Estate Reports for housing costs (4) ArcGIS Near tool (5) Public Authority for Civil Information demographic data (6) Kuwait Municipality plans and interviews for new city data	Migration push–pull factors, segregation, urban planning policy	(1)Empirical observations
Anderson [47]	Secondary, theory	(1) Literature on wellbeing and microeconomics (2) UN Refugee Agency datasets	Well-being theory, microeconomic production and consumption theory, information diffusion, social network theory, systems theory	(1) Decision-making theory (well-being) (2) Heuristics (3) Microeconomic expected utility
Cai [48]	Theory	(1) Literature on systems science and economics	Consensus theory, dynamic multi-agent systems theory	(1) Microeconomic expected utility
Chesney [49]	Teory	(1) Literature on modern slavery as a management practice	Modern slavery as a management practice theory (Crane), nexus of labor exploitation and sustainable business	(1) Decision-making theory (management theory) (2) Heuristics (3) Microeconomic expected utility

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Entwisle [50]	GIS, secondary, theory	(1) Nang Rong project survey and ethnographic data (2) University of Delaware Center for Climate and Land Surface Change 1900–2008 Nang Rong datasets (3) Thai Rice Exporters Association 2000 Nang Rong crop market prices datasets (4) Literature on neo-classical economics theories of migration (5) GIS maps	Migration push–pull factors, neo-classical economic theories of migration, sociological theories of migration	(1) Empirical observations
Espındola [51]	historical, theory	(1) Literature on two-sector (rural and urban) economic theories and production theories (2) Literature on historical trends in developing economies	Migration utility maximisation theory, production function theory	(1) Microeconomic expected utility
Fu [52]	secondary, theory	(1) Literature on other ABMs that explore the economics of migration (2) Literature on probability theory (2) 2000 China Census	Theory of cumulative causation of migration, substantive theories (causes of migration)	(1) Decision theory (cumulative causation) (2) Empirical observations (3) Heuristics (4) Microeconomic expected utility
Garcia- Diaz [53]	Theory	(1) Literature on economic and labor theories	Social network theory, utility maximisation theory	(1) Ising model (discrete choice)

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Hailegiorgis [54]	GIS, historical, theory	(1) Literature socio-cognitive behavioral theories (2) Historical rainfall data for Ethiopia 1901–2009 (3) GIS data	Protective motivation theory, socio-cognitive behavior	(1) Heuristics (2) Psycho-social and cognitive (climate change)
Hassani- Mahmooei [55]	Cited research findings, secondary, theory	(1) Bangladesh Bureau of Statistics data on migration flows (2) Secondary research on Bangladesh district boundaries demographic variables economic variables and development variables (3) GIS data (4) Literature on migration decision making specific to the Bangladesh context and more broadly	Migration threshold theory	(1) Heuristics
Henry [56]	Theory	(1) Literature on economic theories related to common-pool resource use and cooperation	Cost/benefit tradeoffs, present vs future payoffs, theory of discount rates and resource exploitation, game theory	(1) Heuristics (2) Microeconomic expected utility
Ichinose [57]	Theory	(1) Literature on the evolution of cooperation and the Prisoner's Dilemma game	Prisoner's Dilemma, cooperation theory, coevolutionary games	(1) Decision-theory (game theory)
Janssen [58]	Case studies, historical, theory	(1) Literature on social–ecological systems (2) Palmer Drought Severity Index historical SW USA rainfall data	Climate-induced migration, population dynamics	(1) Heuristics (2) Microeconomic expected utility

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Kniveton [59]	Primary empirical, secondary, theory	(1) Literature on climate change induced migration (including other ABMs) (2) Enqueˆte Migration Insertion Urbaine et Environnement au Burkina Faso (EMIUB) nationwide representative survey dataset (3) Focus group interviews conducted across Burkina Faso (4) United Nations World Population Prospects projection data (5) European Centre for Medium Range Weather Forecasts (6) Literature on the Theory of Planned Behaviour	Multi-causal migration theory, individual agency, theory of planned behaviour	(1) Psycho-social and cognitive (Theory of Planned Behavior)
Kniveton [60]	Primary empirical, theory	(1) Enqueˆte Migration Insertion Urbaine et Environnement au Burkina Faso (EMIUB) nationwide representative survey dataset (2) ENSEMBLES project climate projections (3) Literature on the Theory of Planned Behaviour	Theory of planned behaviour	(1) Empirical observations (2) Psycho-social and cognitive (Theory of Planned Behavior)

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Mena [61]	Cited research, GIS, satellite imagery, secondary	(1) Longitudinal and cross-sectional farm and household survey data (2) 1986 LULC classification of Landsat TM satellite imagery dataset (3) Ecuadorian GIS maps (4) Literature on migration	Environmental migration, complexity theory	(1) Empirical observations
Naivinit [62]	Erimary empirical, historical, secondary	(1) Participatory ABM building workshops with stakeholders (2) Qualitative interviews and focus group discussions (3) Survey with farmers (4) Bangkok National Statistical Office Ministry of Information and Communication Technology (5) Bangkok Office of Agricultural Economics Ministry of Agriculture and Cooperatives (6) Historical rainfall data(1986–1995) (7) Historical Thai Rice Mills Association rice market prices	Participatory methods	(1) Empirical observations

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Naqvi [63]	Cited research, GIS, secondary, theory, secondary	(1) Literature on low income economies (2) Pakistan Household Expenditure Survey (3) Pakistan Agriculture Census of 2010 (4) Food and Agriculture Organization (5) World Bank (6) Federal Bureau of Statistics Government of Pakistan (7) Pakistan GIS maps	Utility maximisation migration theory, gravity model of migration	(1) Heuristics (2) Microeconomic expected utility
Naqvi [64]	Cited research, GIS, reports, secondary, theory	(1) Literature on micro household adaptation strategies in the face of natural disaster-like shocks (2) Food and Agriculture Organization (3) Asia Development Bank (4) World Bank (5) Federal Bureau of Statistics Government of Pakistan (6) Pakistan GIS maps (7) United Nations	Micro-adaptation strategies, natural disasters, economic loss models	(1) Heuristics (2) Microeconomic expected utility
Raczynski [65]	Theory	(1) Literature on gregarious effect and other migration theories	Herd behaviour	(1) Heuristics (2) Microeconomic expected utility (3) Psycho-social and cognitive (gregarious or 'herd' effect')

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Silveira [66]	Theory	(1) Literature on rural–urban migration theory	Expected utility theory, rural–urban migration theory, production function	(1) Ising model (discrete choice)
Simon [67]	Secondary, theory	(1) Mexican Migration Project dataset 1990–2013 (2) Literature on small world network topology (3) Literature on social network theory and new economics of labor migration theory	Social network theory, new economics of labor migration (target savings)	(1) Microeconomic expected utility
Smith [68]	Primary empirical, secondary, historical, theory	(1) 'Where the Rain Falls' survey data in Tanzania (2) Meteorological Station data (1950 & 2010) (3) Literature on climate change and migration	Bounded rationality theory, theory of planned behaviour	(1) Heuristics (2) Psycho-social and cognitive (bounded rationality and social feedback)
Suleimenova [69]	GIS, secondary	(1) Armed Conflict Location and Events Database (2) UNHCR camp population datasets (3) GIS road data from Bing Maps	Conflict affected migration	(1) Empirical observations (2) Heuristics
Tabata * [70,71]	Theory	(1) Literature on the interregional migration theory and the socio-economics of migration	Bounded discrete domain, theory of interregional migration, socio-dynamics	(1) Microeconomic expected utility

Table 6 (continued)

First Author (Year)	Data type(s) [listed alphabetically]	Data source(s)	Theory basis or relevant background themes	Decision model(s) [listed alphabetically]
Walsh [72]	Primary empirical, GIS, secondary	(1) Longitudinal social survey of ~ 10 000 households (2) Archive of satellite images to characterize land use/land cover change trajectories (3) Thailand GIS maps	Land change science, decision under uncertainty	(1) Empirical observations
Wu [73]	Cited research, secondary	(1) Research findings on historical temperature and precipitation (2) Research on China's historical migration waves (3) Scientific Databases of China	Social network theory	(1) Heuristics (2) Microeconomic expected utility

*The models presented in Tabata's papers [70,71] are identical by most of the points extracted for this review

ing profits or payoffs, such as wage differential motivated migration). Or in some cases, there might be some use of empirical data, but the data are often insufficient to inform all the decision-making processes so theoretical knowledge is used in combination with empirical observations. For example, Alghais, Pullar and Charles-Edward used primary empirical survey data from urban residents in Kuwait on their residential preferences to determine empirically informed decision rules for why, when and where individual agents would migrate to new urban centers [46]. Decision-making was also the primary focus of Klabunde and Willekens's review and they give an extensive description of the different decision models currently being used in migration ABMs similar to the decision models described above. This review borrows some of Klabunde and Willeken's decision-model categorisations in Table 6 [2]. All eight studies that collected primary data also incorporated these data into the ABM's decision model. Microeconomic utility maximisation has been a long-standing theory applied to the study of migration motivations and decision-making and was used to model decision-making in 12 of the included studies (See Table 6). As Klabunde and Willekens's review points out, there are also key theories pertaining to both individual and group decision-making and pyscho-social and cognitive behavioral science that are increasingly being applied to the study of migration, such as the Theory of Planned Behaviour [2]. In our review, four studies described the using a range of specific decision-making theories in their decision-model choices, which covered broad topics of well-being [47], management [49], cumulative causation including the role of social influences [52], and game theory [57]. Additionally, both of the Kniventon et al. studies applied the Theory of Planned Behavior, which is considered a psycho-social and cognitive theory and described in further detail in Klabunde and Willekens's review [2]. Three other studies described the use of a psycho-social and cognitive theory in the decision model. The psyco-social and cognitive theories incorporated the influence of climate change [54], the herd effect [65], and a combination of bounded rationality and social feedback [68]. Commonly used decision models were simple heuristic models ($n=13$) that were not always informed by any primary empirical findings nor based on clearly defined theoretical knowledge.

3. Model development characteristics

ABMs incorporate the attributes and interactions of agents, time, space, environment, and in some cases social networks and exogenous factors. The majority ($n=21$) of the included studies defined the time-steps in terms of real time ranging from 1 h to 5 years and the time horizons ranging from 4 days to 10,000 years (See Table 7). The 10,000-year time horizon was a far outlier since it was a historical anthropological migration study. Most of the studies had time horizons that were 50 years or shorter. Seven of the studies used time scales that reflected real historical or date ranges, primarily in years, such as Kniventon, Smith and Black's model on climate induced migration in Tanzania from 1970 to 1994 [60]. The remaining models that included clear explanations of time-steps ($n=4$) represented these discrete increments as 'time-to-event' meaning that they represented distinct processes, such as farming seasons or migration cycles [51, 53, 56, 57].

Table 7 Model development: time, space, agents, exogenous characterizations

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Alghais [46]	5-years, 35-years (Real years: 2015 to 2050)	Real: Kuwait city and surrounding urban districts	(1) Resident Agents: nationality, age group, servant or non-servant, migration preferences, household size (2) Household Agents: size, nationality	(1) Districts: type (residential, mixed or other uses), population capacity, suitability parameters, existing services, location (2) Migration push and pull factors: land/property value, housing shortages, commuter traffic and accidents, public services, employment, house size (3) Government planning authority	(1) Households: groups of individual agents

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Anderson [47]	One-hour, 4-days	Artificial construct: Virtual model of a refugee camp	(1) Refugee (Citizen) Agents: health, medical center attendance, socio-economic status, well-being, needs, religion, ethnicity, ideology, time till death, (2) Leader Agents: [same attributes as refugee agent], level of influence, type of influence, ideologies, opinions (3) Governmental Agents: type (army, police, legislature, executive, politicians, etc.)	(1) Medical center: capacity, probability of death (2) Community level: sanitation, food supply, water supply, medical resources, medical personnel, security (3) Social influences: organizations, leaders, media (4) Population: probability of sickness	(1) Organizations: structured group of citizens (members) and leader agents- the combined behaviors and interactions of members and leaders results in the behavior for the organization (2) Intra-group Social Networks: members can form levels of affinity towards each other and influence each other's attitudes (3) Inter-organization Networks: organizations can share attitudes and resources
Cai [48]	One-day, 30-months	Abstract: Two-sectorial urban–rural economy	(1) Worker Agents: propensity to migrate, perspective of wage differential	(1) Quantity of firms and farms (2) Wages	(1) Random social graph topology

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Chesney [49]	One-day, 200-days	Abstract: Social network (not described in detail)	(1) Employer Agents: number of workers needed, number of workers employed, wages paid, profits, employment reach (2) Workers Agents: job status, length of unemployment, movement ability, tolerance for low pay	(1) Industry labor demands	(1) Employer Network: Links between employers representing lines of communication between neighbouring farms- an employer's number of neighbors impacts the wage changes based on wage comparisons (2) Worker Network: Links among workers representing workers meeting and sharing information with each other

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Entwisle [50]	One-year, 25-years	Real: Nang Rong, Thailand	(1) Individual Agents: demographics, probability of in-migration, probability of out-migration (2) Household Agents: assets, land ownership, centrality in village networks, number of ties to wealthy households (3) Village Agents: aggregate of household and land parcel attributes, population size, migration prevalence	(1) Land parcels: status (owned/ managed/ used), size, distance from village, flooding potential, land use, soil suitability, productivity (2) Climate conditions (3) Population: migration probabilities	(1) Households: made up of individuals (2) Villages: groups of households (3) Social Networks: ties among households or villages
Espındola [51]	Time-to-event, 100-time-steps	Abstract: Two-sectorial urban–rural economy	(1) Worker Agents: location, employment, wages, satisfaction level	(1) Urban share of environment (2) Landscape quality (3) Minimum wage	Not described
Fu [52]	One-month, 5-years (Real years: Jan 1996- Dec 2000)	Abstract: Social network on a matrix grid	(1) Individual Agents: demographics, education, origin, migration status, destination, propensity to migrate	(1) Provinces: type (rural/ urban), local economy	(1) Social Network with various levels: empirical and theory based family ties, ties within villages, ties between villages, ties between migrants

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Garcia- Diaz [53]	Time-to-event, ~ 150-time-steps (not clearly described)	Abstract: Lattice grid with 8-cell neighborhoods	(1) Migrant Worker Agents: demographics	(1) Work sectors: type, quantity, expected and actual wages, goods prices, probability of employment, labor-to-output elasticity, labor supply (2) Population: social influence, migration probability	(1) 8-cell neighborhoods: influencing factor on migration decision making
Hailegiorgis [54]	One-day, ~ 50-years (18,250 time-steps)	Real: South Omo Zone, Ethiopia	(1) Household Agents: land, crop and livestock production, climate prediction, ingenuity level, learning rate	(1) Climate: cost of adaptation, risk elasticity (2) Herding: consumption rate, livestock price, destocking rate, livestock growth rate (3) Farming: costs, labor efficiency (4) Vegetation: rainfall minimum, vegetation hectares (5) Population: number of households (6) Demographic changes: birth and death rates	Not described

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Hassani- Mahmooei [55]	One-month, 50-years	Real: Networked districts, Bangladesh	(1) Individual Agents (representing group of people): migration threshold	(1) Districts: socio economic development, population density, climate shock vulnerability (2) Climate changes (3) Population: socio-economic changes (by location)	(1) Agent-to-Agent Links: individual-level interactions and perceptions of social networks affects agents' adaptation decisions
Henry [56]	Time-to-event, ~ 150 (time-steps not clearly described)	Abstract: Singular grid (size unspecified) representing one shared resource area	(1) Individual Agents: level of group cooperation, value of future payoffs, maximum harvest, cost of living, wealth	(1) Resources: discount rate, maximum unit withdrawal, minimum harvest, resource stock, growth rate, defector harvest monitoring (2) Demographic changes: birth and death rates (3) Population: altruism	(1) Common Pool Resources (CPRs): a collection of agents that depend upon a shared natural resource
Ichinose [57]	Time-to-event, 10,000-time-steps	Abstract: Lattice grid with 8-cell neighborhoods	(1) Individual Agents: type (cooperator or defector)	(1) Population level: density, temptation to defect	(1) 8-cell neighborhoods

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Janssen [58]	One-year, 10,000-years	Abstract: Torus grid with 400-cells	(1) Individual Agents (represent group of people): location, food storage available, length of food storage, debt, debt tolerance, sharing strategy, migration threshold	(1) Climate and soil: rainfall, soil degradation, soil regeneration (2) Resources: depletion rate, production, minimum food, maximum debt, storage time, storage loss, learning factor (3) Migration: expectation threshold, opportunities, minimum buffer (4) Demographic changes: birth and death rates (4) Cells: production quality	(1) Settlement: more than one agent in a cell- agent to agent resources sharing (2) Settlement Network: settlement to settlement links- settlements exchange resources when one or more settlements experience shortages
Kniveton [59]	One-day, 50-years	Real: Burkina Faso (all regions)	(1) Individual Agents: demographics, assets, context, previous experiences, perceived peer opinions, perceived behavioral control, biases	(1) Climate conditions (2) Asset distribution (3) Demographic changes: birth and death rates (4) Origin: population size, season, rainfall (5) Destination: population size, choice	(1) Agent-to-Agent Links: information is shared amongst agents- preferences of peers may influence decision making

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Kniveton [60]	One-year, 25-years (Real years: 1970–1994)	Real: 5 regional zones, Burkina Faso	(1) Individual Agents: demographics, location, probability of migration (by zone), previous experiences	(1) Climate conditions: rainfall	(1) Small-World Network: each agent linked to fifty other agents defined at startup- agents inform each other on their migration decisions and peer opinion values are derived for each of the migration options being considered
Mena [61]	One-year, 25-years (Real years: 1990–2015)	Real: Lattice grid laid over Ecuadorian Amazon	(1) Individual Agents: demographics, household	(1) Landscape (cells grouped into 'parcels' and parcels grouped into 'farms'): land ownership, land use, physical environment, landscape type (2) Historic prices: agriculture (3) Demographic changes: birth and death rates	(1) Households: made up of individual agents, one on each farm

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Naivinit [62]	One-day, 10-years	Artificial construct: Farm environments consisting of paddy fields and human settlements (houses, village, city)	(1) Individual Agents: demographics, migration experience, labor status (2) Household Agents: farmer type, income, farm input cost, annual area of paddy for self consumption (3) Village Agents: daily wages paid	(1) Demographic ranges: ages for farmers and migrants (2) Land: transplanted and harvested areas, transplanting thresholds, rainfall thresholds, wages, group (early or late-maturing), crop stages and dates, average paddy yield, age of seedlings, duration of transplanting dates, prices for various paddy qualities, water quantity threshold (3) Water tanks: soil–plant system deductions, minimum depth, actual depth, height of ponding tanks, water level	(1) Households: groups of individual agents (2) Villages: groups of households

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Naqvi [63]	One-day, 360-days	Artificial construct: Representation of Pakistan region with spatially defined cities (3) and villages (9) connected via a road network	(1) Owner Agents: self-producing labor, money, capital stock, food/tradable goods, wages paid (2) Worker Agents: employment labor, money, food/tradable goods	(1) Land: production capacity (2) Employment: total hired workers, wages	(1) Agent-to-Agent Interactions: either within a location (village or city) or across locations
Naqvi [64]	Half-day, 600-days	Abstract: Lattice grid with overlaying road network (Pakistan GIS road map)	(1) Individual Agents: location, income, savings, food supply	(1) Road network: routes, bottlenecks, distances (2) Locations: villages or cities with stocks of workers (3) Earthquake fault line, damages, labor losses, capital losses (4) Population: worker productivity, access to information (5) Market factors: market selling prices, wages	Not described

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Raczynski [65]	One-day, 2,190-days & 7,390-days	Artificial Construct: Fictitious region (8 named sub-regions: California, Manhattan, Yellowstone, Illinois, Acapulco, Los Angeles, Alaska, and London)	(1) Individual Agents: ethnic group, information, location, migration memory, migration threshold, migration cost threshold	(1) Demographic changes: birth and death rates (2) labor market: migrant influx, job opportunities (3) Region: population (per ethnicity), security, water and electricity supply, drainage, paving, technology, climate, infrastructure, services, jobs (4) Organization influencers: type (social, religious, or political structures), impact on migration	(1) Social/Ethnic Groups: demographics, literacy levels, bilingual levels, economic levels, birth and death rate

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Silveira [66]	Not clearly described, ~ 50–100-time-steps	Abstract: Lattice grid with two-sectorial urban–rural economy where cells represent sector-type not spatial distribution	(1) Worker Agents: sector, utility of migration	(1) Urban manufacturing: firm output, total employed workers, worker effort, equilibrium unemployment rate, urban population, manufactured goods prices, scarcity of manufactured goods, job allocation (2) Rural farming: real wages, rural population, agricultural goods prices, scarcity of agricultural goods	(1) Social Neighborhoods: workers are influence by their nearest neighbors

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Simon [67]	One-year, 24-years	Abstract: Social network (not described in detail)	(1) Individual Agents: origin, location, wealth, consumption, total savings, previous migrations, expected wage value, wage at destination, remittances, utility of returning to origin	(1) Wages: wage assignments, wage variables, immigrant labor supply, wage competition, wage equilibrium (2) Migration: immigration policy, financial costs of migration, cost of return, probability of migrant entry to destinations	(1) Small-World Network: high clustering like regular networks but also small path lengths like random networks, all ties are considered to be strong, median number of ties is 6 (2) Agent-to-Agent Interactions: individuals abroad relay information on wage variables to network ties at home to derive utility calculations, migrants send remittances, agents at origin can only obtain information about host country conditions from the migrants they are connected to through network ties

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Smith [68]	One-month, 30+ years (Real years: 2015–2047)	Not described	(1) Individual Agents: demographics, migration history, propensity to migrate, migration attitudes (2) Household Agents: land, economic activity, crop and livestock yields for consumption and sale, income, savings, employed members, employment level, dependency ratio, migrant members, sum of migration experience, migrant remittances, permission for members to migrate	(1) Climate: rainfall (2) Changes to labor markets and food production (3) Demographic changes: birth and death rates	(1) Households: groups of individuals (2) Social and Farm labor Networks: allows agents to share views on migration and a means to distribute farm labor between members of the community through household to household communication
Suleimenova [69]	One-day, Burundi: 396 days (1 May 2015—31 May 2016), CAR: 820 days (1 Dec 2013—29 Feb 2016), Mali: 300 days (29 Feb 2012—25 Dec 2012)	Real: Geographic maps of conflict locations, roads and camps in Burundi, CAR and Mali	(1) Refugee Agents: probability of migrating, location	(1) Environment: routes, road length, border points, border closures, location types, location attractiveness, forwarding hubs	Not described
Tabata * [70, 71]	Not described	Abstract: Discrete sections (not clearly described)	(1) Individual Agents: location	(1) Cell characteristics: density of agents, utility of cell (2) Cost of migration	Not described

Table 7 (continued)

First author (Year)	Time-steps, Time-horizon	Spatial characteristics	Agent types: agent attributes [micro characteristics]	Exogenous or environmental characteristics [macro characteristics]	Social networks [meso characteristics]
Walsh [72]	One-year, 25-years	Real: Geographic map of Nang Rong District	(1) Individual Agents: demographics, migration status	(1) Landscape (cells grouped into 'parcels' and parcels grouped into 'farms'): land ownership, land use, physical environment, landscape type (2) Historic prices: agriculture (3) Demographic changes: birth and death rates	(1) Kinship Networks: the first degree links are an individual's parents and spouse- then additional social network ties are created through matrix multiplication (2) Household Networks: aggregation of kinship networks
Wu [73]	One-year, 2,002-years (Real years: 2 A.D.- 2003)	Abstract: Lattice grid with 227×297 cells in 8/16/24 cell neighborhoods, Residential Unit cells and River cells	(1) Individual Agents: location	(1) Residential units: state (null, potential, existent), population size (2) Provinces: agriculture productivity, area availability, population (3) Migration rate (4) Sub-systems: social influencers, climate, agriculture	Not described

*The models presented in Tabata's papers [70, 71] are identical by most of the points extracted for this review

Spatial characteristics are often an important design decision in ABM and the spatial representation depends on the research aims and data available (See Table 7). Some used abstract spatial representations, such as grids or networks ($n=14$), some used artificial constructs, such as a refugee camp setting or generic farm landscapes ($n=4$), and finally some used real spaces often mapped using GIS data ($n=9$). One study did not describe the spatial elements in enough detail to classify.

Along with time and space, deciding the agents and respective attributes is key to ABM development. Often the aim is to make models as complex as they need to be but no more, often referred to in the ABM modeling community as Occam's Razor principle or the KISS principal ('Keep It Simple, Stupid') [79]. This can be a difficult aim to achieve when deciding how many distinct agent types are needed and what attributes are required for the various decision-making processes and interactions included in the model processes. Most of the models included in this review only have one type of agent ($n=15$), sometimes named as migrants, or workers. Some models include a second or third type of agent, such as employers, land owners, leaders, or government agents and still some models used secondary groupings of individual agents to represent households or villages with their own unique attributes (See Table 7). Most often, these agents have a range of heterogeneous attributes, such as demographics, socio-economics, propensity to migrate or act, assets, etc., but in three of the studies, agents were only characterised and distinguished by location and not by any additional attributes [70, 71, 73].

The models also described various exogenous or environmental characteristics that impacted on the parameters of the model or the agent's behavior within the model. Some examples included, location-specific variables, such as population levels, services available, distance to travel, wage differentials, housing capacity at destinations, etc. (See Table 7). A common exogenous factor was weather or climate ($n=8$), often varying across scenarios or time-steps. Finally, some demographic and epidemiological rates were defined at the population level, such as birth rates, death rates, migration rates, sickness rates, etc. These exogenous or environmental factors are not within the individual agent's control and reflect the larger system(s) that these migration- or work-related decisions are taking place within. Another broader model characteristic that impacts individual agent actions are the social networks that agents can be grouped into, such as households, villages, intra-group networks, and non-spatial social networks. A majority ($n=21$) of the studies used some type of agent grouping or network in addition to individual agents (See Table 7).

4. Model process

The model process takes on a very unique form for every ABM. It would be impossible to fully synthesize the initialization, model steps, decision rules, agent actions and scenario descriptions across all 28 studies in a meaningful way. We recommend the reader inspect the columns of Table 8 to get an overview of the design of the model process as it is simulated in each model. Most of the models

Table 8 Model process: initialisation, model steps, agent actions, scenarios, and stochasticity

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Alghais [46]	(1) GIS spatial data and demographic data are input, population projections are loaded (2) The model schedule is set to begin in 2015 (3) New cities and the districts are assigned suitability weights and threshold for opening the new cities (4) New residents are allocated to old districts with available housing capacity (5) ABM user selects which scenario (1–3) will be simulated	(1) Establishing a new city (2) Migration: Resident agents move from the old urban area to the selected city (3) Segregation distribution: After the end of each time step the nationality segregation level will be calculated and the output map will be updated	(1) Resident Agents (above 18 and not servants): decide whether to migrate, choose destination, migrate (2) Teenagers and Servants: follow household decision	(1) Government scenario: Simulates the urban development of new cities based on the government's plans alone. (2) Resident scenario: Simulates urban development of new cities based on the resident preferences, segregation is simulated according to the resident responses, (3) Global Cities scenario: Simulates urban development of new cities based on the resident preferences, segregation is simulated according to the Global Cities plan	Deterministic

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Anderson [47]	(1) Agent's desire of each need is initially based on the socioeconomic class of the citizen	(1) Agents and networks interact and exchange influence (2) Citizen Agents remain in one of four health states for a minimum of one time step and each time step they check to see if they should transition to another health state (3) Citizen Agents perceive their need satisfaction and adjust weights as certain needs become more significant	(1) Citizen Agents: motivated by individual traits and well-being, receive information, perceive needs, assess deprivation of needs, adjust weights of needs based on the environment, focus on attaining most deprived needs, transition between health states, enter Medical Centers, die (2) Leader Agents: influence ideologies (3) Media Organization Agents: report information, set policy agenda	Not described	Deterministic
Cai [48]	(1) Social graph topology is generated randomly (2) Initial ratio of urban population is set to 20%	(1) Each worker reviews their situation and decides whether to migrate or stay, (2) Some workers migrate, (3) Some emigrating individuals die and some settle at ransom in one of the 8 nearest cells to their origin cell	(1) Worker Agents: review situation, decide whether to migrate, migrate	Not described	Stochastic: network links

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Chesney [49]	(1) Set number of workers and employers populate model and no one is initially employed (2) A randomly selected employer begins model process by offering work to workers within his proximity vision (3) Employers wage levels are set randomly to start	(1) Employers ask workers if they want to work, (2) Workers decide on whether to accept or refuse work offer based on their length of unemployment and experience with the Employer. Workers accept any offer from an employer who they believe will pay at least as high a percentage of the minimum wage as their tolerance (3) Employers should pay every worker a minimum wage but some pay less than this by making unreasonable reductions or simply refusing adherence ot minimum wage. The decision on what to pay comes from the employer's perceived legitimacy of paying under the minimum wage, which is determined by (a) what neighbouring employers pay and (b) whether they are able to employ their full workforce from their potential workforce, which is the number of workers within their locality. Employers' heteronomy moderates both of these (4) There is a probability of workplace inspection each time-step and if an Employer is found to be paying illegal wages they are shut down and replaced with a new Employer (5) Revenue is calculated for that time	(1) Employer Agents: make job offers, set wages, interact with neighbor employers, assess neighbor employer wages, assess workers in proximity (2) Worker Agents: accept or reject job offers, move locations, share information with workers, learn the reputation of employers	(1) Presence of an employer that always pays below minimum wage, (2) Presence of an employer that always pays above minimum wage	Stochastic: probability of visit from labor inspector

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Entwisle [50]	(1) Village, household and individual agents are populated in the model, (2) Land parcels and cells attributes are assigned by GIS data, (3) All attributes are set as null initially, (4) Social data is created using socio-mix (parent/child and spouse/spouse)	(1) Each household makes a choice about how to use its land parcels (for rice, sugar, or cassava cultivation) and inputs such as fertilizer (2) Annual crop productivity is determined based on crop type, soil type and quality, amount of rainfall and planting time, and fertilization levels (3) Crop yields influence household income, (4) Household income affects accumulated assets, (5) Assets affect migration probability, (6) Out-migration is a result of individual probability compared to a random number and if the probability is higher than random number the individual migrates, (7) If a parent dies then assets go to a randomly selected child of that parent, or next to any child in the village, or to any living migrant or to the closest relatives (8) If the risk of household split is positive then new household is created with 15% of original households assets and then is assigned a randomly set land split trigger value	(1) Individual Agents: born, marry, give birth (female agents only), die, migrate, return home, establishing new local residence, send remittances (2) Household Agents: rent or own land, accumulate assets, pass assets to kin when they die or reach old age, choose how to use land parcel, apply appropriate fertilizer	(1) Reference ‘‘normal weather’’ scenario, (2) 7 years of unusually wet weather, (3) 7 years of unusually dry weather, (4) 7 years of extremely variable weather, (5) Remove individual characteristic effects from the model, (6) Remove remittance transaction effects from the model, (7) Remove social network effects from the model, (8) Allows households to adapt to consecutive years of extreme climate and income losses	Stochastic: probability for migration

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Espındola [51]	(1) Workers are randomly placed in a square lattice (2) The initial value of the minimum wage is set to zero (3) The initial urban fraction of the total population is 20% (4) The potential migrant starts the comparison process with a initial satisfaction level set to zero	(1) Agents assess their current situation and consider migration options, (2) Agents choose whether or not to migrate based on wage differentials, (3) Agents migrate (if they decided to), (4) A new configuration of the system is set *The whole procedure is repeated until a preset number of steps is reached	(1) Worker Agents: review sectorial location, determine satisfaction level, make migration decision, migrate, earn wages	Not described	Deterministic
Fu [52]	(1) Agents are populated in their rural origin	(1) Network edges are sequentially added between individuals at all levels (family, villages, provinces, and destinations) using the probability of connection (2) Agents decide whether to migrate based on social influences and individual propensity for migration (3) Agents migrate (if they decided to), (4) The network updates to include new migrations	(1) Individual agents: assess migration options, decide whether to migrate, migrate	(1) No social networks, migration decisions are only influenced by the economy and individual attributes, (2) Implicit social network using origin migration prevalence, (3) Explicit social network that includes evolution of social interactions and migration	Stochastic: probability of families connecting

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Garcia- Diaz [53]	Not described	(1) An Act-share of the total population is enabled to migrate, (2) Every agent in the potential migrants group decides where to migrate based on difference in expected earnings and the agent's social network contacts' locations, (3) The agricultural sector only operates in rural areas and employs all the available rural population (i.e., there is no rural unemployment). The modern and informal sectors only operate in urban areas. Rural residents have no chance of obtaining modern-sector jobs, but once they migrate their chances increase (4) Employment vacancies are filled first with available preferred individuals who have priority over non-preferred ones	(1) Migrant Agents: assess past information, assess expected earnings, assess location of neighbors, decide whether to migrate, migrate	Not described	Stochastic: modern-sector wages

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Hailegiorgis [54]	(1) 50,000 households are input into the model	(1) Rain falls on land parcels, soil moisture levels are updated (2) After the rainfall update, the vegetation subroutine is executed, by growing or shrinking, depending on moisture available, (3) Households conduct livelihood activities, update profiles, and assess the success or failure of its actions. A household decides whether or not to adapt in response to anticipated climatic conditions for the season, including the potential to migrate (4) Each household chooses its adaptation strategy by combining herding and farming, in some proportion, depending on what yields the highest return (5) After the household routine, the herd sequence is invoked	(1) Household Agents: predict rainfall, interact with agents, decide whether or not to adapt, make migration decisions, allocate resources to livelihood activities, monitor wealth, update memory	(1) Mean annual rainfall with "normal" onset for the region, (2) Droughts included at various frequencies (every 5, 10, or 15 years), (3) Extreme events in consecutive occurrences at various frequencies (every 5, 10, or 15 years), (4) Erratic climatic conditions incorporating both good and bad years	Stochastic: household rainfall predictions

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Hassani-Mahmooei [55]	(1) Initial population of 12,317 Individual-Agents spread across 64 districts	(1) Each agent considers the push and intervening factors and makes a decision on its migration (2) If an agent decides migration is beneficial it then measures the pull factors for all the districts in its 100-km radius and then moves to the closest district with the best socioeconomic conditions in accordance with equation (3) The household size is used to determine natural population growth across the districts	(1) Migrant Agents: perceives social network, makes adaptation decision, makes migration decision, migrates, remembers previous migrations	Various scenarios with increasing trends for climate shock occurrence probability distributed across the districts	Stochastic: intervening factor in decision making
Henry [56]	(1) User specifies a number of grids and a total number of agents (2) Agents are assigned uniformly at random to grids (3) Series of independent Common Pool Resources (CPRs), populate the model and are set with initial attributes (4) Initial agent behavior set as cooperative with other agents	(1) Agents make harvesting decisions based on expected payoffs (2) Agents extract from the resource and add to their existing wealth (3) Agents pay their subsistence cost (4) Optionally, discount rates are updated (5) Optionally, migration occurs (6) Each resource grows at the established rate	(1) Individual Agents: assess harvesting payoffs, decide harvesting amount, extract resources, pay costs, migrate	(1) Baseline, (2) Migration is costly, (3) Agents change their discount rates after migration	Stochastic: decision on amount to harvest

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Ichinose [57]	(1) Individual agents are randomly distributed over the square lattice (2) Half of the agents are set to be cooperators and half set to defectors (3) Population density is set and remains constant throughout a simulation run, since individuals will never die or be born	(1) Each site is either empty or occupied by one individual. Empty sites represent spatial regions that individuals can migrate to (2) Agents count the number of defectors in their neighborhood to decide which distance to migrate to (3) Agents then migrate to a random cell within the maximum distance they have calculated. If there is no empty site at that distance then the agent stays in its current location (4) After migrating the agent plays the prisoner's dilemma game with its neighbors and receives any payoffs from the game (5) After completing the game agents update their cooperate/defect strategy to match whatever strategy received the highest payoff.If there were no individuals in the neighborhood to play the game with then the agent retains their current strategy	(1) Individual Agents: count defectors in neighborhood, decide whether to migrate, decide where to migrate, stay in origin, plays prisoner dilemma game with neighbors, gains payoffs, changes strategy	Various population density scenarios	Stochastic: mutations in individual's choices

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Janssen [58]	(1) Agents are randomly allocated to the landscape (2) Initial agent attribute values are drawn from uniform distributions with a one-third probability of having one of three sharing strategies	(1) Each settlement receives rainfall (2) The individual harvest of agent is defined by the rainfall and the agricultural production quality of a cell (a function of soil quality, population size, and technology) (3) Harvesting: Every agent harvests their chosen amount (randomly selected between sustainable amount and maximum) (4) Sharing: Sharing occurs between agents (5) Exchange: Exchanging of resources between agents selected (6) Migrate: Some agents migrate if they assess their resources are too low (7) After calculating the sharing of food for all agents in all settlements, the model starts calculating the exchange of resources between settlements	(1) Individual Agents: harvest, share, exchange, migrate, consume, store surplus, have offspring, die, network with agents, sense rainfall, evaluates other locations	(1) Baseline, (2) Independent Sharing Mechanism: no sharing among households within a settlement, (3) Pooling Sharing Mechanism: all storage and harvest is pooled each year and distributed equally, (4) Restricted Sharing Mechanism: household surplus is shared with households who have shortage till they meet the minimum requirement	Stochastic: rainfall level

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Kniveton [59]	(1) The initial experience rate of an agent is directly retrieved from the dataset on model startup	(1) Agents can be born, marry or die each time-step and in all time-steps agents age (2) Agents decide whether to migrate (3) The migration decision undertaken by agents only occurs once a year at the end of the wet season in September	(1) Individual Agents: move around environment, interact with agents, interact with environment, develop intentions to migrate, migrate, marry, die, communicate migration decisions with peers, returns home	Varied scenarios of future demographic, economic, social, political, and climate change in a dryland context	Deterministic
Kniveton [60]	(1) Population intiatiate with 4,449 agents	(1) A rainfall condition begins, (2) Individual agents weigh their 5 migration options (3) An agent migrates if it is within their perceived means	(1) Individual Agents: weigh migration options, assess if migration is in their means, migrate	(1) Above-average rainfall, (2) Normal rainfall, (3) Below-average rainfall, (4) No population growth, (5) Low-population-growth, (6) Medium-population-growth, (7) High-population-growth	Stochastic: determining perceived means for migration

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Mena [61]	(1) The landscape and social agents are intialized from the survey data (2) Individuals are put into households and households are assigned farms	(1) At each time-step there are demographic changes to the population (births, death, marriages) (2) Assets are calculated for each household in each time step (3) If the household has positive assets then the household decides any land use changes for the next time period also taking into consideration consumption for that period (4)If the household has zero or negative assets then a certain number of people on the farm will out-migrate to find work and send remittances home (no land use change occurs)	(1) Individual agents: grows older, gives birth, gets married, dies, interact with landscape, interact with other agents, changes land use type, migrates, sends remittances (2) Household agents: makes all decisions for individual agents, copies neighbors actions	Not described	Stochastic: migration
Naivinit [62]	Not described	(1) Households decide all Rainfed Lowland Rice-producing activities (2) Rice variety is selected, (3) Establishment of new Rainfed Lowland Rice nurseries and production of seedlings (4) Transplanting and harvesting occur (6) Households update their net incomes and members update their age and migration experiences, (7) Individuals decide whether or not to migrate (8) Individuals migrate	(1) Household Agents: make RLR decisions, adapt to time constraints, hire farm workers, assess available farm work, interact with other households (2) Individual Agents: decide whether or not to migrate	(1) Baseline scenario, (2) Various labor availability (e.g. cheap foreign labor), (3) Various water availability (e.e. no water constraint)	Deterministic

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Naqvi [63]	(1) Each owner is endowed with an initial level of fixed capital stock which is capable of producing a maximum output (2) The initial values are set for the number of agents, maximum daily land production capacity, output self-produced by owners and wage rate	(1) Owners can sell goods in their location, in other locations in the region, or export the surplus based on profit expectations, (2) Workers in each location can stay in their current location or migrate to other locations based on expected income gain (3) Owners self-produce a fixed level and hire workers for the remaining output in exchange for wages (4) Workers buy food for immediate consumption and store small amounts for future income shocks	(1) Owner Agents: self-produce goods, hire workers, make profits, pay wages, sell goods locally, export surplus, store, consume (2) Worker Agents: decide whether or not to migrate, buy food, store food, consume	Not described	Stochastic: determining the migration destination

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Naqvi [64]	(1) Wage rate is set to a value of USD 0.25 per unit of output per day (2) The baseline marginal propensity to consume food out of income is set at the higher end of 0.9 out of current income, the marginal propensity to consume non-food goods out of income is fixed at 0.05 (3) The desired number of days, the food inventories are held, is assumed to be 10 days (4) Initial village and city population levels are set to pre-shock conditions	(1) The migration and market selling procedures act as stabilizing mechanisms across the region (2) These trade-offs between distance and welfare gains are continuously evaluated by agents in the model. Agents check their earnings, produce goods to earn more or check for more favorable locations to migrate to for a higher real income gain. If real income differences across locations are minimal, workers stay at their current location (3) Agents also check their food consumption each time step in order to then buy, store, or consume as needed	(1) Individual Agent: consume food, store food, buy food, check destination payoffs, decide whether to migrate, produce goods, sell goods, earn income, location selection	(1) Higher probability of migration, (2) Lower probability of migration	Stochastic: location choice

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Raczynski [65]	(1) Agent's initial attributes and position in the region map are assigned (2) Each region is set with initial job opportunities	(1) Agents have the potential to move in three different ways: random moves, spontaneous migration or migration actions (2) Agents are looking for the region, which maximizes the migration criterion (3) Agents with higher socioeconomic level are more reluctant to migrate (4) Agent can migrate several times and can hold memory of regions they visited in previous migration trips (5) The distance between the regions can also impact the likelihood of migration between regions (6) The length of stay is determined by how long (in average) an entity will stay in the region where the agent has just migrated. If the average is negative or zero then the agent can migrate again immediately, (7) The model includes a gregarious effect (herd instinct) whereby people are influenced by their peers	(1) Individual Agents: random move, spontaneous migration, decided whether to migrate, migrate, re-migrate, store migration memories	(1) With gregarious (herd) effect, (2) Without gregarious (herd) effect	Stochastic: agent random-move action

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Silveira [66]	(1) All workers are randomly distributed in the lattice (2) 20% of the population is urban	(1) A set probability of worker review their sectorial location and become potential migrants in each time step (2) All potential migrants make the migration decision based on expected wage differentials between their present sector and future (3) As soon as the potential migrants end their reviewing process, a new sectoral distribution is obtained	(1) Worker Agents: paid wages, decide whether to migrate, migrate	(1) Agent decisions are guided by deterministic private utility (expected urban–rural wage difference), (2) Agent decisions are guided by the deterministic private utility and the social private utility, (3) Agent decisions are guided only by the social private utility	Stochastic: job placement and utility function

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Simon [67]	(1) Agents are assigned to a site on the square lattice	(1) Agents originate from a single location and can migrate to one of two destinations (2) Migrants weigh destination choice based on network benefits and expected wages (3) Having chosen their destination, agents at the origin will migrate if their accumulated wealth in the current year is larger than or equal to the cost of migration (4) Migrants evaluate policy conditions and their probability of attaining a visa, (5) Migrants attempt migration (6) Once abroad, all agents spend their yearly wages, on food and lodging (consumption). They may also send remittances (7) All agents have an equal chance of re-migrating	(1) Individual Agents: decide whether to migrate, migrate, decide whether to return home, return home, attain visa, earn wages, spend wages, consume, send remittances, re-migrate	(1) Random networks, (2) Regular networks	Stochastic: assigned networks

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Smith [68]	Not described	(1) Individuals make the migration decision and the decision is mediated by the household's ability to finance the migration (2) Household resilience is determined by income and food production each month (3) For a household to accept farm laboring opportunities, they must be made available by another household within the simulation (4) For a household to be able to invest in migration, the surplus remaining each month following subsistence must be greater than the cost of opportunistic migration (5) Household determine their willingness to send migrants	(1) Individual Agents: decide whether to migrate, migrate (2) Household Agents: determine if they can finance migration, accept farm laboring work, offer farm laboring work	(1) Baseline weather, (2) Dry weather, (3) Wet weather, (4) Extra dry weather, (5) Extra wet weather	Deterministic

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Suleimenova [69]	(1) GIS mapped environment and migration routes are set up (2) Initial sets of refugees are placed in conflict locations	(1) New refugees are inserted into their location of origin (a conflict location) (2) Agents travel a certain number of links (0 +) each based on their move-chance (probability to migrate). In traversing between locations, refugees take major roads, which are shortest journey paths identified using route planners (3) If a refugee reaches the end of a link but has travelled less than 200 km on that day (i.e. one time step), then a new move-chance calculation (and possible move) is performed (4) At varied time-points borders might close and refugees might need to re-route	Refugees Agents: decide whether or not to migrate, decide where to migrate, migrate	(1) Burundi conflict, (2) Central African Republic conflict, (3) Mali conflict	Stochastic: probability of migration

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Tabata* [70,71]	(1) Agents are randomly assigned to domain sections	(1) At each time-step agents consider migration, (2) Agents either migrate or stay in their current location based on utility calculations, (3) Each agent chooses one section at random at each time-step and compares the utility of the chosen section with the sum of the utility of its current section, the cost of migration and a named constant (representing the cost incurred in deciding whether or not to relocate within each time interval) to decide whether or not to relocate within the time interval, (4) If an agent moves from one section to another, then it needs to bear the cost of moving in a real world, (5) The population density is updated	(1) Individual Agents: decide whether to migrate: migrate, pays cost of migration, chooses destination	2003: (1) Agents take only the present behavior of agents into account, there is a fixed number of agents, (2) Agents relocate based on considerations of agents future movements, there is no limit on the number of agents 2004: (1) Utility is defined as an increasing affine function of the density of agents, (2) Utility is equal to a concave quadratic function of the density of agents	Stochastic: utility of migration

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Walsh [72]	(1) Creation of social agents, land objects, and characteristics such as population migration, crop yield levels, and landscape settings	(1) At each time-step there are demographic changes to the population (births, death, marriages) (2) Assets are calculated for each household in each time step to determine land use, land use changes, moves to other nearby farm or migration (3) Households can interact with other households to learn from their farming actions (4)If the household has zero or negative assets then a certain number of people on the farm will out-migrate to find work and send remittances home	(1) Household Agents: change land-use, move farms, send migrants	(1–9) Different monsoon scenarios	Stochastic: migration

Table 8 (continued)

First author (Year)	Initialisation	Model steps and decision rules	Agent types: agent actions	Scenario simulation	Deterministic or stochastic: model component that is stochastic
Wu [73]	(1) All cells are initialized in null state (2) 60 million individuals are assigned to 31 provinces using historical data	(1) Cells collect environmental information to update their states (2) The choice to migrate is influenced by larger macro elements of climate change, potential agricultural productivity change, and waves of mass migrations (3) Individual agents who decided to move out of a unit choose their destination province by roulette wheel arithmetic based on the attraction between the other provinces (4) After migrating, agents select an inner cell (residential unit) randomly within the destination province and check whether the target cell is suitable for living and has capacity, if not then the agent continues to float and chooses a new target in the province (5) Cellular and provincial data are updated after agents migrate	(1) Individual Agents: decide whether to migrate, migrate, choose destination province, selects province cell, assess cell suitability and capacity, floats, settles in cell	(1) No external disturbances occur, (2) Climate change occurs, (3) Climate change and the Yongjia Migration occurs, (4) Climate change, the Yongjia Migration, and the Anshi Migration occurs, (5) Climate change, the Yongjia Migration, the Anshi Migration, and the Jingkang Migration occurs, (6–9) Only one of the 4 migrations is considered: Yongjia, Anshi, Jingkang, or HuGuang	Stochastic: cell destination

*The models presented in Tabata's papers [70,71] are identical by most of the points extracted for this review. The differences in the models have been captured in the 'Scenarios' column

are initialized by constructing the real or abstract spatial setting and populating it with agents set with initial attributes and locations. A commonly repeated theme throughout the models is that an agent primarily decides whether or not to migrate, where to migrate and then attempts to execute migration. In most cases, this decision to migrate is based on a microeconomic utility function, as described in Table 6. Most of the studies ($n=22$) included a variation of 'scenarios' which usually entailed changing exogenous elements or altering decision rule variables, most commonly this was changes in weather scenarios, but in some cases it was not weather-related, such as differences in employee wages [49] or differences in urban development plans [46].

Table 8 also indicates whether the ABM is deterministic ($n=6$) or stochastic ($n=22$), stochastic means that it includes some element of randomness (through specifying probability distributions) in determining agent actions, social network composition, or some element other than the initialization settings. One example of the inclusion of a stochastic process can be found in the Entwisle et al. model where an individual agent's propensity to migrate is compared to a randomly drawn number and if their propensity to migrate is higher than that number then they migrate [50]. Uncertainty in decision-making is pertinent to low-wage labor migration where the migration planning can be unsystematic and the outcomes not guaranteed. Introducing some randomness in decision-making and the migration process reflects some of this uncertainty in outcome. This approach can also model that there is the possibility of divergence from expected decision-making behaviors in some cases due either to natural variability in behaviors or uncertainty, which is an acknowledgement that we might not be aware of all the heterogeneous agents' considerations.

5. Model analysis

Finally, we reviewed the main output variables in the analysis of the models, whether or not the authors conducted uncertainty or sensitivity analysis (according to the authors), and if and how the model was validated, again, in the authors' own words (See Table 9). We also extracted the model assumptions and study limitations as described by the authors (See SM-3).

In total, ten studies mentioned some sort of sensitivity testing. Most of these detailed variation testing for a select number of key variables, two studies described using a probability distribution functions of key parameters approach to testing key variables [47, 52]. When assessing whether or not the models were validated, we relied on the authors' accounts of analysis intended as a form of validation analysis. Twelve studies mentioned some form of model validation (See Table 9). Validation is a challenging task when there is a scarcity of reliable or comparable real-world data. Anderson et al. and Entwisle et al. compared their model outputs with research on a similar topic but using different methods, logistic regression and a system dynamics model, respectively [47, 50]. Three articles, Fu and Hao, Hassani-Mahmooei and Parris, and Wu et al. all compared the output of their models to available census or population data and Naqvi also compared model outputs to a relevant secondary dataset [52, 55, 73]. Chesney et al. considered validation of the model to be a thorough comparison of whether the model outputs captured the key principles of the Crane's theory on slavery

Table 9 Model analysis: Model outcomes, uncertainty and sensitivity analysis, and model validation

First author (year)	Output variables	Uncertainty and sensitivity analysis as described by the author(s)	Model validation as described by the author(s)
Alghais [46]	Population distribution, internal migration patterns, new city development stages, nationality segregation levels	Not described	Not described
Anderson [47]	Health indicators, number of refugees receiving medical treatment	Levels of food and water were varied while the other four parameters were held constant at their midpoints. Additional runs were performed for each of the other four input variables	Internal model validity was assessed by verifying that its data, variables, and parameters are based on experimentally developed theories such as well-being and data from the UN Refugee Agency. Outcome validity was assessed, predictions from the agent-based model were compared with the predictions from an independent system dynamics model on the same topic
Cai [48]	Distribution of workers	Not described	Not described
Chesney [49]	Contract slavery (paid less than minimum wage), diffusion of slavery	Not described	The model was validated by examining how well it captures Crane's theory on modern slavery as a management practice
Entwisle [50]	Rates of in-migration, rates of out-migration	Not described	Some analytical comparison to a regression-based prediction of the effect of climate change on migration as a counterpoint with which to compare the ABM results. A scenario with the actual recorded weather conditions from 1975 to 2000 was also included This scenario's results were substantially equivalent to those for the reference scenario
Espındola [51]	Urban share, urban unemployment rate, rural–urban expected wage differential	Not described	Not described

Table 9 (continued)

First author (year)	Output variables	Uncertainty and sensitivity analysis as described by the author(s)	Model validation as described by the author(s)
Fu [52]	Social network structure, migration rates, interdependence of network and migration outcomes	The model incorporates uncertainty of parameters by using distributions of parameters	Network changes were validated by comparing the migrant share with the cumulative causation theory of migration that highlights the influence of migrants on non migrants' future moves. Migrant behavior was validated by comparing the model outputs against the aggregate data from the census
Garcia- Diaz [53]	Distribution of workers, spatial effects of social influence, expected wages	Individuals' sensitivity to utility variations was tested	Not described
Hailegiorgis [54]	Population size, migration rates, livestock and crop production, household wealth	Not described	Not described
Hassani- Mahmooei [55]	Migratory paths, population distribution	Not described	The model population projections were validated by comparison with published primary results of the Bangladesh 2011 Population and Housing Census
Henry [56]	Harvesting rates, resource sharing, migration	Not described	Not described
Ichinose [57]	Cooperation, defecting, migration	Sensitivity analysis of the result was conducted over varying mutation rate	Not described
Janssen [58]	Population size, population density, average resource level, agent strategies, strategy evolution	Sensitivity analysis was conducted on the main parameters of the model by varying the parameters from relatively low to high in the uncertainty range	Not described
Kniveton [59]	Migration flows	Not described	A five-run-averaged total migration flows are compared directly with the observed EMIUB record

Table 9 (continued)

First author (year)	Output variables	Uncertainty and sensitivity analysis as described by the author(s)	Model validation as described by the author(s)
Kniveton [60]	Migration flows	Not described	The observed flow of migrants in and from Burkina Faso, as recorded by the EMIUB retrospective multilevel migration history survey is shown alongside modelled migration flows from an ABM for the period 19,701,994
Mena [61]	Mean assets, land-use, migration rates	Not described	Not described
Naivinit [62]	Household income, number of migrants	Not described	One early form of validation was collaborative design of the ABM with local farmers, (2) Expert validation: The BMM model has been recognized by the participating farmers as a sufficiently accurate representation of their current situation. These farmers were confident enough in the model's form to be able to articulate it and present it in academic settings to researchers
Naqvi [63]	Number of workers, rural population, worker, food price, daily income, income savings, food consumption	In order to assess the sensitivity of the model to various shock levels, we perform multiple simulation runs for food production shocks ranging from 50 to 75% in steps of 5%. Sensitivity bands are generated from 10 simulation runs per shock	Not described
Naqvi [64]	Real income, food price, savings rate, percentage starving, income distribution, consumption distribution, displacement, population dispersion	The model is tested for parameter sensitivity for pre-shock outcomes and loss function sensitivity for post-shock outcomes	Initial pre-shock conditions are validated through comparison with available secondary datasets, but this could not be done for the post-shock model data

Table 9 (continued)

First author (year)	Output variables	Uncertainty and sensitivity analysis as described by the author(s)	Model validation as described by the author(s)
Raczynski [65]	Migration flows	Not described	Validation is limited, as acknowledged in the limitations, but the authors made some comparison to similar migration flows in Australia, New Zealand and Bangladesh
Silveira [66]	Distribution of urban/rural workers, expected wages ratio	Not described	Not described
Simon [67]	Migration flows, destinations, length of migration, number of migrations	Sensitivity tests were conducted by varying parameters, such as number of ties at home and utility for return. Sensitivity testing was also conducted for the sample size and some of the model assumptions	Not described
Smith [68]	Migration flows, household resilience	The probability function approach was used to explore the sensitivity of the modelled system to changes in the shape (non-scaled normal or sigmoid) and scale (point at which optimal yield is achieved) of the relationship between rainfall, livelihood/food security and migration	Not described
Suleimenova [69]	Total refugees, refugee dispersal	The sensitivity to the move-chance variable, conflict locations, attractiveness value for camps, and for conflict zones were tested	The average relative differences are presented between the ABM prediction results and the UNHCR refugee camp registration data. The results were also compared to the Mean Absolute Scaled Error (MASE) relative to the six other techniques
Tabata [70, 71]*	Migration	Not described	Not described
Walsh [72]	Crop yields, migration, household assets	Not described	Not described

Table 9 (continued)

First author (year)	Output variables	Uncertainty and sensitivity analysis as described by the author(s)	Model validation as described by the author(s)
Wu [73]	Agent relocations	Not described	To test the validity the Scenario 1 simulated population of each province is compared with the corresponding real provincial population as of 2003 to see if the model results replicate historical trends of population in China

*The models presented in Tabata's papers [70, 71] are identical by most of the points extracted for this review

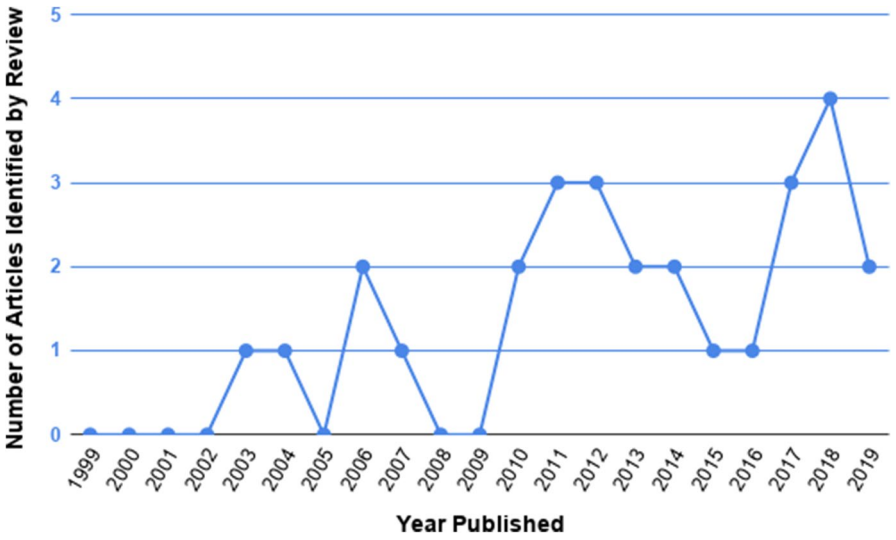

Fig. 4 Included articles by year of publication

as a management practice [49]. In both of the Kniventon et al. studies, the model outputs were compared to the *Enquête Migration, Insertion Urbaine et Environnement au Burkina Faso* (EMIUB) dataset, which was the same dataset used for calibration of the models [59, 60]. Naivinit et al. was the only paper that described using stakeholder validation techniques by having key experts review and critique to model [62]. Raczynski struggled to find any available data for validation so instead showed how the model output trends compared to migration flows in three other contexts [65]. Suleimenova et al. used the United Nations High Commissioner for Refugees (UNHCR) refugee camp registration dataset as one comparison point, but then also used the Mean Absolute Scaled Error (MASE) to compare the model outputs to six other model techniques [69]. Again, it was not within the scope of this review to assess the quality of any aspect of the ABM models, so we have not provided quality assessment of the sensitivity analysis, uncertainty analysis or validation methods reported by the authors of these studies.

In relation to sensitivity or uncertainty of outcome variables, a majority of the studies ($n = 25$) looked at least at one migration indicator (migration rates, population distribution, urban vs rural population shares, etc.). Only one study looked at health-related outcomes [47]. Only one study looked at slavery as an outcome [49]. Ten studies looked at some outcome measurement related to financial or resource utility gain (expected earnings, household assets, crop yields, savings, etc.). Only two studies looked at outcomes related to social network structure (such as network dependence and spatial effects of social influence).

6. Correlations between model aim and model development choices

Similar to Klabunde and Willeken's review and Thober and colleagues' review [2, 4], this review presents a range of unique models in examining both the model

aims and model development processes. Due to the lack in standardised reporting of the model development, it is not straightforward to make conclusions about correlations between model aims and model development choices. That said, Table 10 presents a summary of some critical model development choices that we believe relate to the model's purpose. We have grouped the included publications according to their original study aim categorisation (see Table 5) and presented model characteristics that span model calibration, development and process (Tables 6, 7, 8). While we again acknowledge that some of the reporting on model development choices was opaque, from the descriptions we were able to extract, we have observed a few correlations between study aims and model development choices.

The majority of ABMs exploring environmental-migration links and humanitarian migration used empirical data, this might reflect the highly context-specific nature of research questions on these topics which require in-depth up-to-date familiarity with the regions, geographies, and events pertinent to the real-world questions. Context specific models on the influence of climate change or humanitarian crisis require empirical embeddedness and would be limited in their claims if they relied only on theory to calibrate models. Likewise, most of the environmental-migration ABMs mapped real geographic environments where these environmental-migration-related phenomena are emerging. While the same importance to context-specific data relates to models investigating modern slavery trends of the social dynamics of migration, there are fewer examples of empirically embedded models, which is more likely to be a reflection of data scarcity in these fields and not a correlation to study aim. The majority of the models exploring socially influenced migration patterns used abstract representations of space which is usually a sufficient simplification of this type of model since the question of interest is social spaces and linkages and is not necessarily concerned with how the abstract representation maps to real geographic space. The models in this review use a range of representations of time-steps. Notable correlations we observed were that the humanitarian migration models use shorter representations (hourly, daily) across all the 4 models which likely reflects the acute timelines of humanitarian crises and the aim to understand large-scale human mobility patterns in short time frames. In comparison, the ABMs aiming to explore migration demographic and regional trends more frequently used annual time-step representations to explore human mobility over longer more regular intervals.

In relation to the inclusion of dynamic interactions, it appears that models that aimed to present environmentally motivated migration all include agent-to-environment interactions, likewise models looking at socially influenced migration all include social networks and agent-to-agent interaction. In comparison, fewer of the models on migration demographic or regional trends include these dynamic interactions. Finally, we thought it was pertinent to note that across all the study aim categorisations there was frequent use of model scenario testing. This is not entirely surprising as this is a key feature and advantage to ABM methods, but it is a particularly useful approach to use on research topics that include high degrees of uncertainty often due to data scarcity or rapid adaptations in individual behav-

Table 10 Summary of model aim and model development

Broad research category / First Author (Year)	Data Sources: Empirical (incl. secondary)	Data Sources: Theory	Agents: More Than 1 Type	Spatio-Temporal & Networks: Space	Spatio-Temporal & Networks: Social Network	Spatio-Temporal & Networks: Time-steps	Dynamic Interactions: Agent-to-Agent	Dynamic Interactions: Agent-to-Environment	Scenarios: More Than 1 Type
Economic utility of migration									
Henry (2017) [56]	☐	☑	☐	abstract	☑	time-to-event	☐	☑	☑
Environmental motivations for migration									
Entwisle (2016) [50]	☑	☑	☑	real	☑	annual	☑	☑	☑
Hailegiorgis (2018) [54]	☑	☑	☐	real	☐	daily	☑	☑	☑
Hassani- Mahmooei (2012) [55]	☑	☑	☐	real	☑	monthly	☑	☑	☑
Janssen (2010) [56]	☐	☑	☐	abstract	☑	annually	☑	☑	☑
Kniveton (2011) [57]	☑	☑	☐	real	☑	daily	☑	☑	☑
Kniveton (2012) [60]	☑	☑	☐	real	☑	anually	☐	☑	☑
Mena (2011) [61]	☑	☐	☐	real	☑	annually	☑	☑	☐
Naivinit (2010) [62]	☑	☐	☑	artificial construct	☑	daily	☑	☑	☑
Smith (2014) [68]	☑	☑	☑	-	☑	monthly	☑	☑	☑
Walsh (2013) [72]	☑	☐	☐	real	☑	annually	☑	☑	☑
Humanitarian migration									
Anderson (2007) [47]	☑	☐	☑	artificial construct	☑	hourly	☑	☑	☐
Naqvi (2014) [63]	☑	☑	☑	artificial construct	☑	daily	☑	☑	☐
Naqvi (2017) [64]	☑	☑	☐	abstract	☐	daily (0.5 day)	☐	☑	☑
Suleimenova (2017) [69]	☐	☐	☐	real	☐	daily	☐	☑	☑
Migration demographic or regional patterns									
Alghais (2018) [46]	☑	☐	☑	real	☑	annualy+ (5yr.)	☑	☑	☑
Cai (2015) [48]	☐	☑	☐	abstract	☑	daily	☐	☑	☐
Silveira (2006) [66]	☐	☑	☐	abstract	☑	-	☐	☐	☑
Simon (2019) [67]	☑	☑	☐	abstract	☑	annnual	☑	☑	☑
Wu (2011) [73]	☑	☐	☐	abstract	☐	annual	☐	☑	☑
Espmdola (2006) [51]	☐	☑	☐	abstract	☐	time-to-event	☐	☐	☐
Tabata (2003) & (2004)* [0-71]	☐	☑	☐	abstract	☐	-	☐	☐	☑
Modern slavery									
Chesney (2019) [49]	☐	☑	☑	abstract	☑	daily	☑	☐	☑
Socially influenced migraton									
Fu (2018) [52]	☑	☑	☐	abstract	☑	monthly	☑	☐	☑
Garcia- Diaz (2012) [53]	☐	☑	☐	abstract	☑	time-to-event	☑	☑	☐
Ichinose (2013) [57]	☐	☑	☐	abstract	☑	time-to-event	☑	☑	☑
Raczynski (2018) [65]	☐	☑	☐	artificial construct	☑	daily	☑	☑	☑

*The models presented in Tabata's 2003 and 2004 papers are identical by most of the points extracted for this review.

Table 10 Legend		
Data Sources	☑	**Empirical:** Study described the use of at least one primary or secondary empirical datasource for model calibration (this does not include, published research findings, GIS data, or historical trends in weather data)
	☑	**Theory:** Study described the use of theoretical work to inform the model calibration
Agents	☑	**More Than 1 Type:** Model included different agent types (e.g. migrants and employers)
Spatio-Temporal & Networks	☑	**Space-Real:** Model environment represented a real geographic place (e.g. Northern Thailand), usually mapped using GIS data
	☑	**Space-Artificial construct:** Model environment represented a structured artificial construct (e.g. refugee camp) that did not correlate to a real geographic place
	☑	**Space-Abstract:** Model environment was an abstract space (e.g. a grid or torus ring)
	☑	**Social Network:** Model included explicit links or ties between agents to form a social network
	☑	**Time-Steps:** How the model represented time-steps in real-time or time-to-event
Dynamic Interactions	☑	**Agent-to-Agent:** Model included interactions between agents (e.g. exchanges of information or money, influences from social ties on migration decision, etc.)
	☑	**Agent-to-Environment:** Model included interactions between the agents and the environment or agent information gathering about the environment (e.g. farming land, assessing destination payoffs to make decisions, etc.)
Scenarios	☑	**More Than 1 Type:** Any study that included more than one 'model scenario' that were all tested and compared
Note: '-' = 'information missing'		

iour and population trends, which are both true of research on human migration influenced by many dynamic factors, such as changing environments, acute crises, and evolving social networks.

Limitations

This review does not include structured quality assessments with comparable quality scores. Again, this was partly because the aim of this review was to learn from the methodological approaches not to assess the research findings and the rigor of the findings. As explained in the beginning of the results, models similar to agent-based models but called by different names were excluded for the sake of reproducibility of this review and uniformity in data extraction. We acknowledge that this inclusion criteria may have excluded valuable studies to meet this review's objective and may have introduced a disciplinary bias to this review's inclusion and, therefore, results. To account for this potential loss, we have included these 8 studies in a table in the Supplementary Material (SM-2) for any reader that might be interested to review this specific subset of excluded studies and compare the model development with those included in this review.

This review also did not include some potentially relevant models that have not yet been peer-reviewed but are available on multiple sharing platforms (such as, OpenABM, GitHub, Netlogo libraries). Finally, the large variability in model characteristics makes in-depth synthesis and comparisons of all data extraction points a challenging task. We have attempted and hopefully succeeded at giving a bird's-eye view of the data extraction while not over simplifying the nature of each model by comparing the various elements of the ODD + D framework too broadly.

Discussion

State of the art in ABM in migration and modern slavery research

The aim and contribution of this review have been to summarize the use of ABM for migration and modern slavery research to present researchers and decision-makers with a comprehensive overview of how ABMs on migration have been developed to date, as well as identifying gaps in ABM development and use in the field. This review highlights that ABM is a method increasingly used in migration research as it has been in other social and health science research topics. To date, ABMs in this field have been used primarily to test theories and less frequently draw on primary empirical input. The main theories modeled in the ABMs identified in this review were utility maximisation theory, social network theory and theory of planned behaviour. Across all the ABMs, about half were neither based on empirical data nor on clearly defined behavioural theories. This is very likely a reflection of the scarcity of empirical data and theoretical frameworks on migration that take a complexity science approach. Many scholars working on social ecological modeling have noted this as an issue across ABMs in many disciplines [1].

The ABMs described in this paper commonly recognised the role of social networks in migration, but few used advanced methods of social network analysis to inform the dynamics of network evolution over time and space. We agree with Klabunde and Willken's assessment that there is still a lot of work to be done in integrating network analysis techniques into ABMs [2]. The papers in this review also noted the complexities in the migration decision and processes. However, with the exception of Suleimenova (2017) [69], most models assumed that migrants were "rational agents", for example that migrants knew the target labor markets at destination, that the choice of destination was open and informed, and that deception was not a possibility. Many of these models did not capture all of the core elements of decision-making, notably missing are the evaluation of migration options or complexity in the decision process that Klabunde and Willeken's emphasized in their review [2]. For instance, going back to our earlier example of research on the nexus of low-wage labour migration and modern slavery, none of the labour migration models in this review included the risks of labor exploitation and how this might influence migration decision-making or expected utility calculations. In that respect, these models do not capture the experiences of most low-wage labor migrants globally. The challenge is that there is a knowledge gap on how the risks of labor exploitation or other forms of modern slavery might influence individual behaviors. There are many areas we still do not understand the underpinning mechanisms of entry into modern slavery versus decent work and thus the models trying to represent low-wage labor migration are not transferable to real-world interventions. The choice of stochastic models may compensate to some extent for these knowledge gaps or further unknown heterogeneity in migration behaviours and outcomes. However, it is also important to note that some uncertainty cannot be reduced by acquiring knowledge, such as variability in agents' behaviors. Thus the stochastic variability will always be essential to account for some of these irreducible uncertainties. However,

the consideration of decision-model options and choice is a critical step in ensuring models capture the complexity of real-world processes. Klabunde and Willeken's review provides in-depth recommendations on the way forward to capturing migration decision-models in ABMs. Scholars exploring the intersection of cognition and multi-agent systems have emphasised opportunities to integrate cognitive modelling into social studies addressing complex behaviors that originate in individual perceptions [80].

Additionally, the models' development varied considerably in terms of attributes and interactions of agents, time, space, and environment. The most common model processes involve scenarios where an agent decides whether or not to migrate, where to migrate to, and then attempts to execute the act of migration. Changes in scenarios were introduced in ABMs by changing exogenous elements or altering decision rules, but the majority of these were climate scenarios and these models would benefit from a broader exploration of influences on individual migration behaviors as Bell and colleagues also recommend in their recent review [3].

Finally, many of the ABMs did not undergo validation or sensitivity analysis, which are critical steps to ensuring rigor in ABM methods and confidence in their use to inform policy makers. Model validation is an area of work critical to all ABM practice and methods of empirical validation are still in their infancy as are standardised best practice of model analysis [1, 81]. While there are serious challenges to validating ABMs modeling in data-scarce topics, such as this, there are, nonetheless, validation methods that are feasible and acceptable given these challenges [27]. The major challenge concerns validating the ABM against qualitative data in part because much of these data have not been collected with developing ABMs in mind and it can be difficult to calibrate or validate the decision-rules from these data sources. There is an opportunity for methodological development in translating qualitative analysis for use in ABMs. Even small samples of key expert interviews can be critical in informing the model development and justifying the model design [76].

Future considerations for migration ABMs

Migration complexity research will benefit from studies that collect primary data on migration and migration outcomes, such as modern slavery, with ABMs in mind from the research design conception stage. Going back to our migration and modern slavery example, researchers can collect information specifically about the agents (migrants, brokers, intermediaries, employers), agent-attributes (migration experiences, migration knowledge, resources to migrate), agent-agent interactions (who influences migrants' attitudes toward migration, how migrants meet brokers, how migrants find or change employers at destination), agent-environment interactions (how migrants engage with or avoid institutions managing legal labor migration pathways), and most importantly, how individuals and groups make decisions, learn and adapt (the emergence of preferred migration pathways over time). A further benefit of ABM methods and future consideration in study design is that multiple data sources can be incorporated from several disciplines. This review presents

examples of how ABMs can use multiple data sources, but one method that has been under-utilized in this group of studies is participatory methods with key stakeholder groups and the target population of interest, which have offered critical insights to other nascent fields of computational social science research. For example, the stakeholder approach allows modelers with perhaps in-depth theoretical knowledge on the topic to collaborate with domain experts and triangulate these sources of established theory and current expert knowledge [76]. There was one example in this review that used this stakeholder approach in a series of workshops with Thai farmers to inform the individual behavioural rules of the model to reflect the Thai context. An interdisciplinary approach is critical to be able to integrate theoretical and empirical knowledge of a social phenomenon into a mathematical model [20]. In fact, we concur with the other reviews, future ABM work in this area would benefit from interdisciplinary approaches to every stage of model development to address research questions that cut across social and ecological studies, as well as disciplines such as economics, psychology, geography, and complexity science [2, 4]. Diverse disciplinary and theoretical perspectives will strengthen the real-world likeness of these highly complex, dynamic, and socially embedded models and may present new uses for existing data for model calibration.

Lastly, despite widely accepted challenges and shortcomings to standardising model analysis procedures and model validation, all future ABM studies must critically consider their approaches to these steps, learn from ABM practices across all disciplines, and document the justifications for their analysis and validation choices as well as their process to enable a wider and more synchronised debate on future best practice.

The need for transparent and clear reporting on model development

The model descriptions in the articles included in this review were overwhelmingly opaque with various critical details omitted. This review is not the first to critique the lack of a 'best practice' in reporting model development [1, 4] and as one reviewer noted there are severe limitations to systematic reviews that aim to synthesise findings across a body of studies whose methods cannot be easily compared, not to mention that there is still work to be done to develop standard methods for systematically reviewing ABMs [34].

In this review, there was generally insufficient detail or models were reported without proper sign-posting or terminology that could be understood by most readers. Since few of the studies used recommended development frameworks, such as ODD + D, there was not a structure or fluidity to the way the model choices were reported, which makes it difficult to interpret findings and learn from the methods at a critical stage in methodological development for the field of migration and modern slavery research. This critique is true for ABM research on other topics as well. This review suggests that more frequent use of the ODD + D framework will strengthen future ABM research.

In addition, the methods of sensitivity analysis and model validation were described in limited detail or not covered by the authors, which leads us to assume

that the analysis was either not done or not completed. The findings of the models arguably are then open to substantial criticism regarding their validity and applied usefulness. This weakness is a critical gap in the evidence-base since the topics of migration and modern slavery are priorities on many global agendas, including the beforementioned UN Sustainable Development Goals [6].

Using ABM to address pressing and complex questions in the fields of migration and modern slavery research

Migration is currently a focus of substantial international attention, particularly global economic migration and modern forms of slavery. Policy-makers are seeking a strong evidence-base that can be used to address the myriad aspects of global mobility. Current pressing concerns include migration patterns and trajectories, individual or group vulnerability, and migrant protection and safety. To date, robust evidence to inform policy-making has proven to be weak because individual and population mobility cannot be explained by the exclusive use of methods that assume linear average effects of exposures on single outcomes affecting homogenous populations. The patterns of migration and characteristics of migrants are emergent consequences of many interacting and non-linear, unpredictable phenomena, and this complexity requires an agent paradigm approach [14].

For example, many of the current interventions and policy goals for safer migration are currently relying on extremely simplistic cause and effect assumptions about the exposures that might lead to modern slavery. If we are going to achieve SDG 8.7— "eradicate forced labour, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labour, including recruitment and use of child soldiers"—we must engage with the complexity and dynamics of low-wage labor migration and population-level emergent outcomes (such as widespread labor exploitation) in our research methodologies. For example, the influence of social networks in group decision-making must be explored in greater depth and this will give rise to a greater understanding of how these interactions might hinder the effectiveness of migration interventions that operate on the individual level [28].

To study migration, one has to go beyond simple binaries, such as: domestic or international; documented or undocumented; recruiter facilitated or social network facilitated; forced or voluntary; for asylum or for work, etc. Because migration is a mechanistic and dynamic process, analyses must be able to address this complexity.

Agent-based modeling offers a promising method to improve our understanding of and programmatic responses to these real-world problems. This review offers an overview on how ABM has been used in the fields of migration and modern slavery research and the remaining gaps and potential future uses to advance the application of these methods to inform more effective responses to high-risk migration and modern slavery.

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Data availability The full data extraction table for this systematic review can be found in the Supplementary Material. All data extraction is from the cited articles' text or the articles' supplementary material text.

Compliance with ethical standard

Conflicts of interest This review and its authors do not have any conflicts of interest pertaining to this work.

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