



A systematic review of the impact of food security governance measures as simulated in modelling studies

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To effectively address food security, we need tools that assess governance measures (for example, strategic storage reserves, cash transfers or trade regulations) ex ante. Simulation models can estimate the impact of such measures via scenarios with differently governed food systems. On the basis of a systematic review of 110 simulation studies published over 2000–2021, we examined how food security governance has been represented, and identified needs for future simulation model development. We found that studies commonly used agent-based, system dynamics, and computable general equilibrium models; tended to be production, trade or consumption centric; assessed the impact of a wide variety of mostly treasure- or authority-based measures; and applied diverse food security indicators, mostly of access or availability. We also identified blind spots (for example, simulation of nodal measures) and proposed how to address these blind spots (for example, telecoupling) and to make food security governance simulation studies fit for meta-analyses (for example, harmonizing food security indicators for comparison).

Global food security, the access to sufficient, safe and nutritious food, has declined slowly but steadily since 2015¹. Recently, this decline has accelerated owing to the coronavirus disease 2019 (COVID-19) pandemic and measures taken to mitigate its impact on human health. Millions of people were pushed into immediate hunger, and in the medium to long term, existing inequalities are expected to exacerbate further². To address food security challenges, we cannot rely exclusively on market mechanisms to deliver sufficient quantities of nutritious food at affordable prices. This was illustrated all too well by the world food price crises of 2007–2008 and 2010, which were largely a result of speculative activity in global commodity markets³ and increasing demands for grains as feed and fuel⁴. We need intervention in the form of governance⁵: public (for example, government), private (for example, food retailers) or communal (for example, farmer cooperatives) entities that implement measures to improve food security⁶.

To govern effectively, we need to measure the impact of governance implementation ex post or simulate the impact of governance implementation ex ante. The literature on ex-post assessments of food security governance is too limited to provide empirically founded guidance with regard to choice of governance measures to improve food security^{6,7}. The literature on ex-ante assessment, however, is vast and growing. Ex-ante assessments are made using simulation models that compare scenarios where food systems are governed differently to projected business as usual scenarios⁸. Food security governance simulation studies have the following characteristics: they use simulation models (1) to assess the impact of governance measures ex ante (2) on food security (3) within a food value chain context (4).

There are many types of simulation models, including agent-based, system dynamic, optimization and equilibrium models (for full list, see Supplementary Note 1), which have different capabilities, making them fit for different governance cases and

contexts⁹. Models may be coupled to overcome weaknesses associated with certain model types¹⁰. Governance measures are the tools that governing entities use to affect society¹¹. These can be categorized into: nodality (information dissemination), authority (laws and regulation), treasure (financial incentives) or organization (capacity building, punishment and crisis management)¹¹. Within these categories, measures vary in how socially and spatially targeted they are (Extended Data Table 1). Social and spatial targeting is increasingly adopted around the world in the hope of maximizing impact with limited funds^{12,13}. Socially targeted measures, such as social protection policies^{14–16}, can reach vulnerable groups more effectively¹³. Spatially targeted measures can reach geographically vulnerable groups that, for example, live in drought-prone regions^{17–19} or food deserts^{20–22} more effectively²³. In addition, spatially targeted governance can, through more efficient use of natural resources, contribute to enhanced food production^{24–26}. Assessment of socially and spatially targeted measures does, however, require socially and spatially disaggregated models and data such as household surveys and gridded data, respectively. Most simulation models are not spatially disaggregated by default, and some model types, such as equilibrium models, traditionally rely on socially aggregated data such as trade balance sheets²⁷.

Impacts of governance on food security are assessed with indicators of food availability, access, utilization or stability (for indicators, see Supplementary Dataset 1). Impacts may occur within or outside the jurisdictions within which measures are implemented. A trade moratorium on grains from Russia and Ukraine may, for instance, reduce grain prices in Russia and Ukraine, but increase prices globally, especially in net importing countries²⁸. As both the COVID-19 pandemic and the war in Ukraine have illustrated, capturing such spillover effects is increasingly important in our highly interconnected world²⁹. Simulated changes in food security occur within food value chain contexts, which differ from setting to setting.

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Table 1 | Data extracted from eligible simulation studies during qualitative content analysis

	Variable	Values
Simulation methods	Model type	ABM, CA, SDM, optimization, econometric, CGE, PE, micro-simulation, mathematical other
	Model domain	Bio-physical, economic, logistic, social
	Social data used for calibration	Aggregated quantitative data, disaggregated quantitative data, disaggregated qualitative data
	Spatial data used for calibration	None, spatial points, spatial networks or spatial zones (discrete), spatial gridded (continuous)
Food system	Value chain echelons	Production, distribution, processing, trade, retail, consumption
	Crops, livestock and commodities	Cereals and cereal products, composite crops, composite foods, livestock and animal sourced foods, vegetables and derived products, oil crops and vegetable oils and fats, fruits and derived products, stimulant crops, sugar crops, derived products, additives
Governance	Simulated governance measures	Open ended (for full list, see Table 3)
	Category of governance measure	Nodality, authority, treasure, organization
	Social targeting of governance measure	At-large, group, individual
	Spatial targeting governance measure?	Yes/no
Food security	Food security indicators used to assess governance impact...	Open ended (for full list, see Supplementary Dataset 1; classified according to food security dimensions availability, access, utilization and stability)
	...measured	Within jurisdiction, outside jurisdiction, globally
Spatio-temporal embedding	Spatial scale	≤village, ≤municipality, ≤province, ≤country, ≤continent, >continent
	Spatial resolution	As given in study, transformed to square metres. NA if not given
	Temporal resolution	As given in study, transformed to days. NA if not given
	Countries	Country or countries the modelled system represent. NA if not given

By means of quantitative content analysis information on simulation methods, food system characteristics, simulated governance measures, measurement of their impact on food security, and the spatio-temporal embedding of the models used were coded and collected.

In subsistence settings, they may consist of production and consumption echelons only, but more often than not, middle echelons also play an important role through distribution, processing, storage and packaging, trade and wholesale, and/or retail of food³⁰. Spurred on by widespread urbanization and associated dietary changes, these middle echelons have grown rapidly and continue doing so throughout the Majority World (that is, low-income countries)³⁰. Rapid urbanization without accompanied development of road infrastructure may, for instance, leave urban consumers unable to obtain or afford produce from rural areas³¹. Despite this, the middle echelons tend to be missing in both development initiatives³² and simulation studies³³.

Previous reviews have discussed subsets of above-mentioned characteristics (for example, how to bridge micro-macro scales in food security models^{10,34}) or pointed out the shortcomings of the ex-post literature on food security governance^{6,7}. Yet, no studies have systematically reviewed food security governance simulation studies, providing no community-wide understanding of common modelling practices, potential blind spots and promising developments. In this Article, to facilitate targeted and relevant future model development, we aim to summarize and critically appraise existing food security governance simulation studies, which, in contrast to ex-post studies, have not been systematically reviewed. In particular, we ask how food security governance is simulated. This question, in turn, is broken down into four subquestions: (1) Which modelling approaches are used? (2) How do simulation studies represent the food system, and to what extent are they (capable of) capturing up- and downstream value chain dynamics? (3) Which governance measures are simulated, and are simulation models (capable of) assessing socially and spatially targeted governance

measures? And lastly: (4) How is food security measured, and to what extent are models (capable of) assessing spillover effects?

Results

A total of 1,953 potentially relevant studies were identified through a database search in Scopus and Web of Science (for full list, see Supplementary Dataset 2). Among these, 110 remained after title and abstract screening, full-text reading and qualitative content analysis (Table 1). The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram (Fig. 1) illustrates the selection process of the simulation studies for systematic review (for more information, see Supplementary Note 2, Supplementary Figs. 1–5 and Supplementary Dataset 3).

Modelling approaches. Food security governance was simulated by means of: cellular automata (CA, $n=6$), agent-based models (ABM, $n=25$), system dynamics models (SDM, $n=19$), optimization models ($n=11$), partial equilibrium (PE, $n=11$) and computable general equilibrium (CGE, $n=24$) models, micro-simulation models ($n=7$), econometric models ($n=15$) and/or other mathematical models ($n=13$) (Fig. 2). Thematically, equilibrium and micro-simulation models were mostly economic, while ABM, SDM, optimization and econometric models were more diverse, often covering both the bio-physical and/or the social domain in addition to the economic (Fig. 2a and Extended Data Fig. 1).

While most studies simulated governance using stand-alone models, a minority used coupled models ($n=21$). Coupling to specialist, typically bio-physical, mathematical models to simulate, for example, crop growth^{18,35,36}, hydrology³⁷ or transportation²⁰ occurred among ABM, SDM, optimization, CGE and PE studies.

Further, CGE models were frequently coupled to micro-simulation models to scale down findings, enabling the assessment of governance impacts on different socio-economic groups, for example^{31,38,39} (Table 2).

The spatial scale of simulation studies varied from village to global (Fig. 2b). With the notable exceptions of ABM, CA, and CGE and PE studies, most studies had a national scale. ABMs and CA tended to have subnational scales, simulating governance interventions within provincial or municipal jurisdictions. CGE and PE studies, contrastingly, were often global (Fig. 2b). In terms of geographic focus, there were no obvious patterns distinguishing model types (Fig. 2c).

Overall, two out of the three most food-insecure regions globally, East Asia and the Pacific ($n=43$) and Sub-Saharan Africa ($n=40$), were the regions covered most by the studies reviewed. South Asia ($n=21$), however, received little attention considering the region's high population and food insecurity status (Fig. 2c). Considering individual countries, China ($n=30$) and the United States ($n=26$) dominated. Here, studies reflected national policy, with models covering the United States typically aiming to improve access to healthy food in 'food deserts', poor city districts, through various pricing, safety net or city planning policies^{14,20,22}, and models covering China typically aiming to obtain or maintain food self-sufficiency through, for instance, land protection schemes^{40–42}.

Value chain coverage. No study covered all food value chain echelons, and only two studies^{43,44} covered all value chain echelons but one: retail. Most studies covered food production only, consumption only, or a combination of production, consumption and trade (Fig. 3). Food distribution, processing or storage, and retail were rarely simulated. Value chain coverage by CA, ABMs, SDMs and optimization models was overwhelmingly production centric (Fig. 2d). CGE and PE models, contrastingly, were centred around the trade echelon, often combined with production and/or consumption echelons.

Studies that covered the distribution, processing, storage and retail echelons came in three fashions. Firstly, some ABM studies assessed policies that aimed to improve urban food access by transporting food to the consumers²², or the consumers to the food^{20,21}, or by relocating or creating new supermarkets^{20,21}. Secondly, some optimization and SDM studies simulated measures that aimed to improve the availability and stability of (perishable) foods by, for instance, setting up a bottom-up cooperative for dairy distribution, processing and retail¹⁵, increasing the shelf life of bread⁴⁶ or meat⁴⁷ at retail, using import quotas to strengthen the domestic supply chains⁴⁸, or improving sourcing strategies of public distribution programmes⁴⁹. Lastly, some CGE and PE model studies simulated measures that aimed to reduce poverty and improve food access through investment in transportation^{31,50}, processing⁵¹ or marketing^{50,51} infrastructure.

Governance measures. The governance measures assessed most through food security governance simulation modelling were treasure or authority based (Table 3). Among treasure-based measures, bearer-directed payments ($n=31$) dominated, and among authority-based measures, standard constraints dominated ($n=38$). Frequently simulated authoritarian measures were land protection^{24,40,52}, tax policies^{53–55} and trade regulations such as tariffs^{15,54,56}, quotas^{28,55,57} or bans^{28,43,58}. These measures have in common that they affect or are meant to affect the wider public (first row, Table 3). Infrequent or absent authoritarian measures were conditional tokens⁵⁹ and enablements¹⁶, and certificates and directed constraints, respectively, which are customized for individuals (second and third row, Table 3). Treasure-based measures were more frequently targeted towards groups or individuals than authority-based measures. Social protection policies such as conditional cash

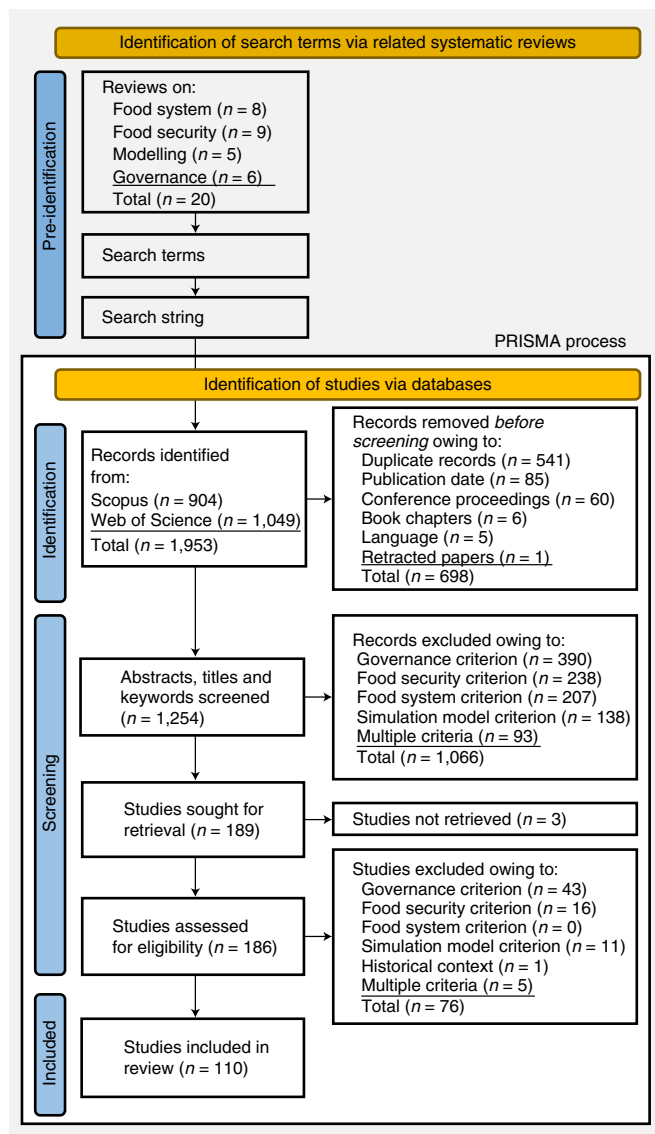


Fig. 1 | PRISMA flow diagram illustrating the identification and screening process. Search terms were compiled on the basis of related systematic reviews, and studies were identified through a systematic search and checked against exclusion criteria.

transfers^{14–16} or food stamps, for example^{60–62}, were specifically targeted towards the poorest, most vulnerable citizens.

Organization and nodality were simulated much less than treasure and authority. Among organization-based measures, at-large treatment (typically, big infrastructure projects such as construction of dams^{63–65} or irrigation canals^{17,65,66}, roads^{31,50} or market facilities^{20,21,50}) was simulated most. Additionally, some studies assessed the impact of governance measures aiming to improve food access through better distribution systems^{39,57,67}. The most common nodal measures assessed were group-targeted messages. These were usually policies through which the government educated^{68–70} or tried to convince farmers of the benefit of certain products^{70,71} or practices^{72–74} (Table 3).

Studies' choices of governance measures sometimes coincided with choices of model types. At-large trade policies relying on authority such as import tariffs on food commodities were, for instance, almost exclusively simulated by CGE^{15,54,56} and PE models^{55,70}. Contrastingly, infrastructure projects and other organizational governance measures were simulated by SDM^{66,75,76},

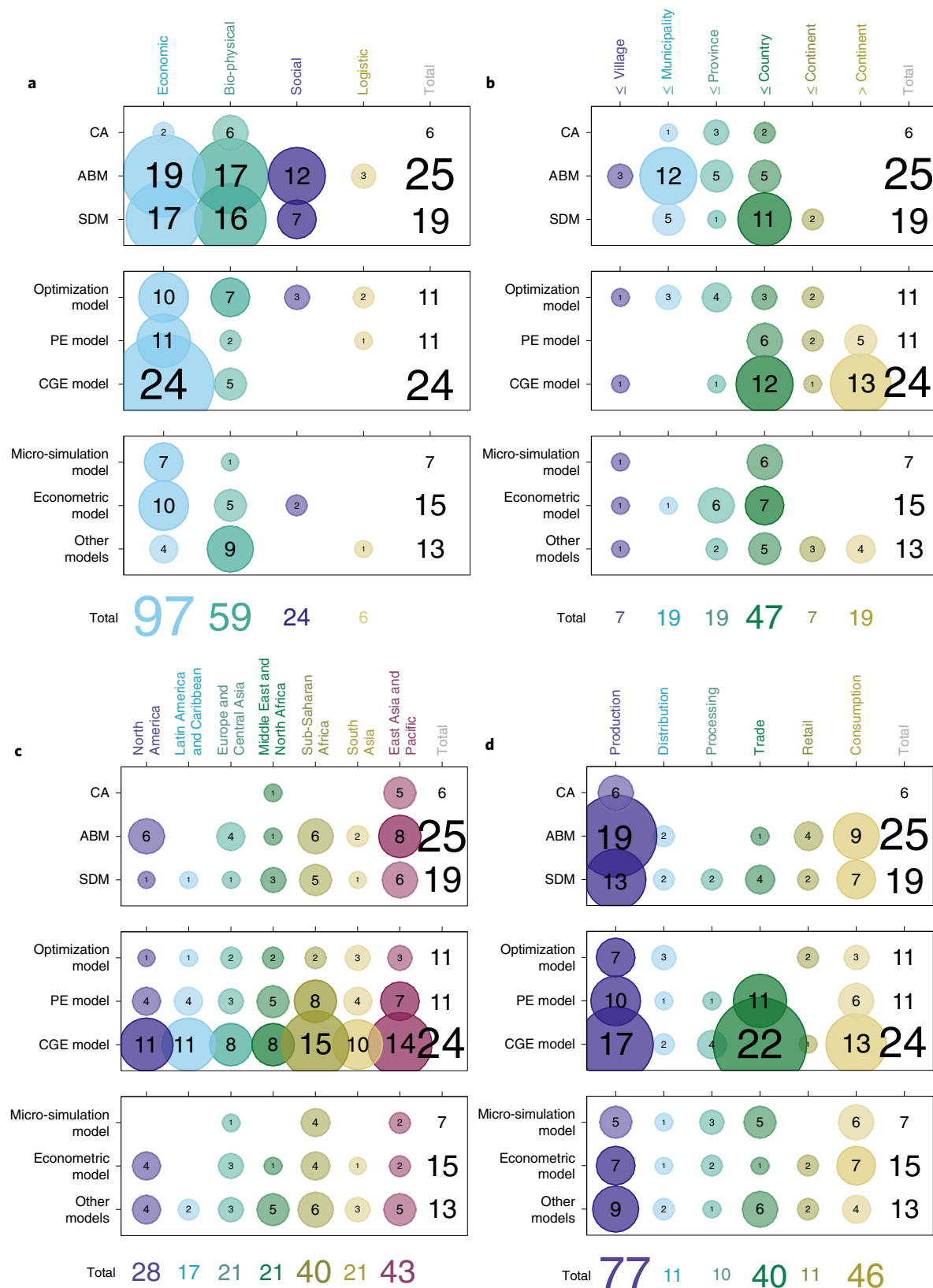


Fig. 2 | Domains, scales, geographic focus and food system representation of different types of simulation models. a–d, Number of studies using models with different modelling domains (a), spatial scales (b), simulated regions (c) and value chain echelons (d). Sizes of numbers and bubbles are proportional to number of studies. If a study covers multiple domains, is multi-scale, simulates or spans multiple regions, or covers multiple value chain echelons, it is counted multiple times.

Table 2 | Use of coupled model types by food security governance simulation studies

	CA	ABM	SDM	Optimization model	PE model	CGE model	Micro-simulation model	Econometric model	Other model
CA	3 ^{25,40,84}			1 ⁷³				2 ^{42,52}	
ABM		20 ^{14,19,21,22,36,63,65,67,72,80,81,108–116}	1 ⁸⁷					1 ¹⁸	3 ^{20,117,118}
SDM			17 ^{24,45,46,48,66,69,74–78,85,119–123}						1 ¹²⁴
Optimization model				8 ^{49,50,59,125–129}					2 ^{47,64}
PE model					9 ^{28,43,55,61,70,71,91,130,131}				2 ^{37,132}
CGE model						17 ^{16,17,44,51,53,54,57,58,82,83,88,90,133–137}	5 ^{15,31,38,39,138}		2 ^{35,56}
Microsimulation model							1 ¹³⁹	1 ⁶⁰	
Econometric model								11 ^{68,79,96,140–147}	
Other model									3 ^{26,62,148}

The numbers refer to the number of simulation studies that use (combinations of) different model types. Note that the diagonal in the table shows the number of studies with uncoupled models, not models coupled to models of the same model type.

ABM^{20,63,65} and optimization^{49,50,64} models. Nodal measures were mostly simulated by ABMs and SDMs^{74,77,78}, as well. Treasure-based measures such as subsidies on farm inputs were, however, simulated by the full range of model types. Socially targeted governance measures, too, were simulated by the full range of simulation models (Fig. 4a and Extended Data Fig. 2a). Spatially targeted governance measures were rarer than socially targeted governance measures, but were also simulated by most model types (Fig. 4b and Extended Data Fig. 2b).

To be able to assess the impact of socially and/or spatially targeted governance measures, models need to be socially and/or spatially disaggregated. We found that most studies ($n=65$) were able to identify food-insecure socio-economic groups within the wider study population, and most of these studies also simulated governance measures that targeted these people directly ($n=41$; Fig. 4a). Most of these were treasure based. Socially targeted governance measures relying on organization, and especially nodality and authority, were much rarer (Table 3). Most studies did not use spatially disaggregated data ($n=68$), rendering them unable to identify vulnerable geographic groups (for example, inhabitants of drought-prone regions; Fig. 4b). Among the spatially disaggregated studies, few ($n=14$) explored the potential benefits of spatially targeted measures that could potentially reach these vulnerable groups^{17–19} or enhance production through more efficient natural resource management^{17,25,26} (Table 3 and Fig. 4b). Further, our review showed that some studies simulated targeted measures with models calibrated using socially ($n=14$) and/or spatially ($n=12$) aggregated data only (Fig. 4). Bazzana et. al.⁶⁵, for instance, assessed the impact of the construction of hydro-electric dams, electric grids and water canals, and payments as compensation to those who lost resources because of these infrastructure projects. Despite the spatially targeted nature of these governance measures, the assessment was made without using any spatial data, without reporting the spatial extent or resolution of the model and without providing a spatially disaggregated visualization of the impact of the governance measures.

Governance impacts. Governance impacts on food security were most frequently assessed using indicators for food access (44%) or availability (27%). Few studies assessed the impact of governance on food utilization ($n=39$), and even fewer on the nutritional qualities of crops ($n=1$)⁶⁸ and diets ($n=3$)^{37,72,79}. The number of studies that assessed the impact of governance on stability was also low ($n=29$),

but as many studies (also) provided indicator values over time ($n=41$); in total, more than half of the studies assessed stability. However, most models had too low temporal resolution ($\geq$ annual) to account for seasonal differences. In total, 123 different food security indicators were used (Supplementary Dataset 1). The majority of these (60%) were unique to single studies. The price of food commodities ($n=38$) and income of citizens ($n=37$) were most frequently used to assess the impact of governance on food access. The production of food ($n=33$) and the area used to grow crops or keep livestock ($n=26$) were most frequently used to assess the impact of governance on food availability. The consumption ($n=21$) or purchase ($n=6$) of food were most frequently used to assess the impact of governance on food utilization. Lastly, self-sufficiency ($n=8$) and stocks ($n=8$) of food crops were most frequently used to assess the impact of governance on stability. Only a minority of the studies ($n=23$) captured changes in the distribution of food security within a population through indicators such as poverty incidence ($n=13$), or income inequality ($n=9$), though a few additional studies gave insight into inequality ($n=8$), for example, by providing the incomes for different socio-economic groups^{31,80,81}. Most indicators were assessed only within the jurisdiction where the governance measures were implemented ($n=90$), that is, potential spillover effects were seldom captured. When the impacts were assessed globally ($n=14$), or locally outside a jurisdiction ($n=12$), this was done by PE^{28,37,55} or CGE^{54,82,83} simulation studies.

Discussion

A wide variety of governance measures have been simulated in the reviewed studies, though authority- and treasure-based measures were much more frequent than organization-based, and especially nodality-based, measures. Concerning food security governance, there has not been a comprehensive overview of governance measures implemented in practice. Country responses to the 2008–2009 food price crisis were, however, mapped by Demeke et. al.¹³. In line with this systematic review, they found that a lot of authority- and treasure-based at-large trade policies were implemented. They also registered that many countries implemented treasure-based food price regulation policies and social protection measures such as cash and food transfers to vulnerable people, and subsidy schemes aiming to increase food production. However, they did not register any nodality or organizational measures. This might be because, in contrast to the implemented authority- and treasure-based measures,

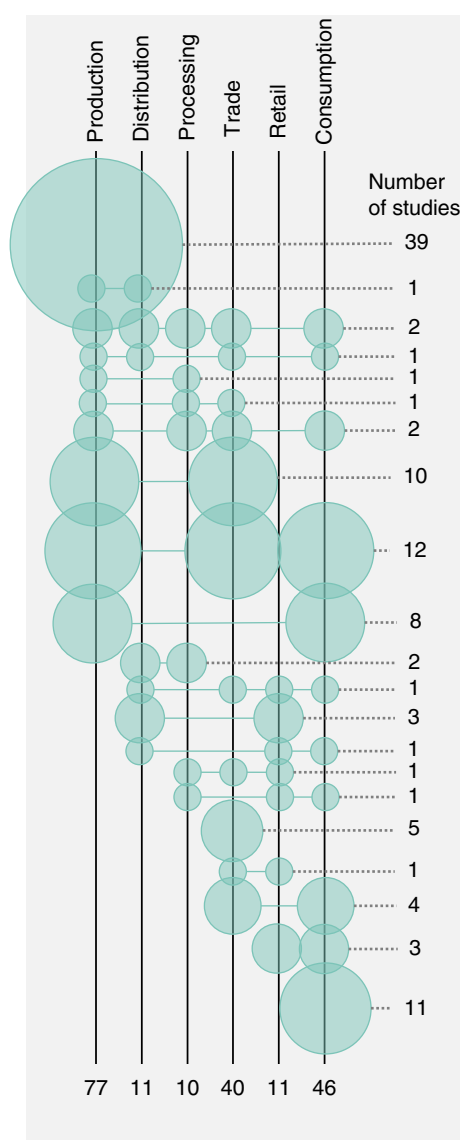


Fig. 3 | Food value chain coverage by food security governance simulation studies. Row numbers and bubble sizes refer to the number of studies that cover the specific combinations of value chain echelons. Column numbers refer to the total number of studies that cover each specific value chain echelon.

they do not provide immediate help in times of crises. Nodality and organizational measures typically require longer time horizons, as they often—though not always—require actors to adopt new knowledge^{54,70,73} or norms^{20,60,84}, or require the construction of large-scale infrastructure^{24,66,76} or logistic networks^{21,49,85}.

As research and practice have thus far focused on treasure- and authority-based measures, the potential of many organizational, and especially nodal, measures remains unexplored. In the field of public health, nodal measures such as mass radio campaigns have been shown to be highly cost-effective, mostly owing to the fact that they are very cheap compared with other health interventions⁸⁶. In the field of food security governance, we found only one realistically simulated example of nodal governance implementation and its effectiveness. This study, performed by Williams et al.¹⁸, found the impact of sharing climate forecasts with farmers (a nodal measure) to be similar to the impact of providing 20% of farmers with jobs (an organizational measure). However, they expected the nodal

measure to be much cheaper and easier to realize¹⁸. The rarity of simulated nodal measures could be due to the fact that this requires models with high degrees of social disaggregation, and the ability to simulate interacting agents, which requires approaches such as ABMs. As increased cost-effectiveness in food security governance could speed up the alleviation of food security, we see the development of such models as an important research priority.

Shifting the focus from spatially untargeted at-large measures based on treasure and authority towards spatially and socially targeted measures based on organization, authority and nodality would be helpful to expand our knowledge base, potentially increase the cost-effectiveness of food security governance and support the decision-making process of policymakers already interested in implementing such governance measures but who often fail to do so effectively^{12,13}. This can be achieved through the use of spatial models such as ABMs^{20,63,87} or CA^{25,40,52}, or by disaggregating traditionally aspatial models such as CGE or optimization models by either parameterizing them differently for different geographic regions^{39,88} or by coupling them to spatial models⁷³. In terms of the assessment of the impact of governance on food security, simulation models tend to assess governance impacts on availability, access and extra-seasonal stability, but rarely intra-seasonal stability, nutrition and social inequality. As these aspects are prerequisites to achieving food security^{5,89}, and their assessment is technically feasible^{18,67,68}, we call researchers to include them in future studies.

Steering away from unwanted, negative spillover effects, that is, reducing food security within a region at the expense of food security outside that region, is another prerequisite to achieving net food security improvement. To avoid spillover effects, studies need to assess the impacts of governance measures not only within the jurisdiction where they are implemented, but also in regions connected to this jurisdiction²⁹. However, only a small minority of studies did this, all using CGE or PE models. Further, only three of the studies capturing spillover effects used socially disaggregated data^{70,90,91}, and only one reported the impacts of governance implementation in a socially disaggregated way⁹⁰. This illustrates that the ability to assess and target governance in a socially disaggregated way and the ability to assess potential spillover effects are rarely combined. Yet, this is crucial for achieving social justice outcomes⁵. To combine these two abilities, we need to bridge the gap between macro- and micro-scale models^{10,92}, by downscaling macro-models or by upscaling^{10,34} or by telecoupling²⁹ micro-models.

Scaling down is a technical development that has opened up for equilibrium models through coupling with micro-simulation models^{39,88}. Scaling up micro-scale models is less common than scaling down macro-scale models⁹³, and none of the models eligible for this review did this. Nevertheless, this is technically feasible and has been illustrated by Niamir et al.⁹⁴, who simulated the energy consumption choices of households with an ABM and upscaled their impact on total EU-26 energy use with a CGE model. Telecoupling, which accounts for socioeconomic–environmental interactions between distant places²⁹, has been illustrated in various food system simulation models. Dou et al.⁹⁵, for instance, used a telecoupled ABM to assess the impact of increased demand for soybeans in China on land use and farmers' welfare in Brazil. However, none of our identified food security governance simulation studies use telecoupling.

Lastly, we found that simulation models typically either have a macro-economic focus and simulate the inter-linked impact of governance on food production and consumption through trade, or focus solely on either the production or consumption end of the value chain (Fig. 3). The governance measures simulated reflect this trend: measures attempting to improve transportation^{20,22,49} and retail^{20,47,67}, and especially storage^{57,62,96} and processing^{45,51}, were rare. The neglect of the value chain echelons between production and consumption is in line with previous reviews—which have

Table 3 | Classification of governance measures

Nodality	Authority	Treasure	Organization
<i>Governance measures targeted towards the wider public (at large)</i>			
Propaganda (n = 7) Water conservation awareness campaign ⁷² Campaign promoting shopping in supermarkets ¹⁴ Dietary guidelines ^{50,84} Campaign promoting walking to supermarket ²⁰ Trainings in waste separation ⁷⁷ Two-child policy ¹⁴⁹ Packaged self-serve messages (n = 2) Education and training ^{69,70} Privished messages (n = 0)	Standard constraints (n = 38) Land protection policies ^{24,40,42,52} Production restrictions for X ⁵⁹ Export taxes ^{53–55,58,91} , bans ^{28,43,58,127} or tariffs for X ²⁸ Import tariffs ^{15,35,53–58,70,82,133,135,136,148} or bans ^{109,127} or other trade barriers ^{57,82,109} for X Import tariffs on farm inputs ^{54,70,136} Value-added tax (VAT) on farm inputs ⁵⁰ or on X ^{138,147} Compliance cost for genetically modified food production ¹²⁹ Land protection policies ^{24,40,42,52} Open compacts (n = 7) Legalize agroforestry in timber production forests²⁵, bio-fuel production on marginal grasslands²⁶, or colonization of new land for agriculture²⁵ Tax rebate ^{55,144} Tax exemptions for farm inputs ¹³² VAT exemptions for X ¹³⁸ Increased shelf life for X ⁴⁶ Open permits (n = 7) Export quotas ^{28,39,43,55,57} or import quotas for X ^{15,48}	Bearer-directed payments (n = 31) Subsidies on farm inputs ^{24,31,51,71,77,78,80,81,88,91,116,118,120,121,124,131,132,146} , farm labour ⁵¹ , energy consumption ⁷⁷ , X (in stores) ^{21,128,137,147} , housing loans ⁷⁷ or land rent ^{51,68,114} Subsidies for purchase/establishment of productive (farm) infrastructure ^{51,80,91,125,131} , processing activities ⁵¹ or marketing activities ⁵¹ Export subsidies for X ^{35,53,56} Reduce price of soon-to-expire products ⁴⁷ Reduce price of healthy products ^{67,79} Bounties (n = 13) Targeted investments in agricultural sector⁸⁸ Direct payments for X production ^{83,108,110,131} Minimum support price for X ^{61,70,73,74,77,83,143,148} or export of X ⁵⁵	At-large treatment (n = 15) Construction of market^{20,50,75}, water^{17,24,63–66,76,123}, energy^{54,65}, or road infrastructure⁵⁰ Disaster control⁵⁹ Rural settlement consolidation⁸⁷ Afforestation ^{69,76} Soil erosion control ⁵⁹ Increase availability of X in supermarkets ^{14,79} At-large processing (n = 4) Dynamic shelf-life policy ⁴⁷ Livestock vaccination campaign ⁸⁵ Increase nutrient content of X during processing ⁴⁵ Sewage treatment ⁶⁹ At-large storage and custody (n = 3) Strategic storage reserves for X ^{57,62,96}
<i>Governance measures targeted towards specific groups</i>			
Group-targeted messages (n = 14) Improve communication/education of agricultural extension services ^{68,78,80,81,146} Farm schools ⁷⁰ Promotion of farm inputs ⁷¹ , technologies ⁷⁰ or techniques ^{73,74} Trainings in the use of farm inputs ⁷⁷ or technologies ⁷⁷ Schools for women ³⁸ Promotion of export of X ⁶⁸ Share seasonal forecasts with farmers^{17–19}	Group-targeted constraints (n = 4) Land reform¹³⁰ Producer tax on X ^{39,53} Ban trade of agricultural land ⁵³ VAT for hotels and restaurants ¹⁴⁵	Conduits (n = 10) Investment in agricultural research and development ^{24,37,38,44,69,70,88,141} or extension services ^{31,38,70,88} Investment in water ^{69,88} , market ⁵⁰ or road infrastructure ^{31,50}	Group treatment (n = 2) Introduction of farmers' markets²¹ Form cooperation ¹¹⁵ Transportation and distribution (n = 2) Improved public transport²⁰ Mobile food market programme²¹
<i>Governance measures targeted towards specific individuals</i>			
Bespoke messages (n = 1) Family planning programme ²⁴	Conditional tokens (n = 1) Farmer-specific production requirements⁵⁹ Enablers (n = 1) Reduced VAT on X for low-income households ¹⁶ Certificates (n = 0) Directed constraints (n = 0)	Contracts (n = 15) Adjust interest rates ^{50,141} Offer off-farm work ^{18,117,118,139} Credit programmes ^{50,68,70,113,117} Credit provision for agricultural production-related expenses ^{36,80,113,118} Forward contracts with X producers ¹¹¹ Redistributive direct payments ^{112,116} Grants for land reform ⁹⁰ Transfers (n = 11) Compensation for resource dispossession^{53,65} Cash transfers ^{14–16} or food stamps to poor, vulnerable people ^{4,73,85,119,134,142}	Transportation and distribution (n = 7) Crowd-shipping food rescue programme²² Ride service for food shopping²¹ Relocation of water demanding cropping systems¹²⁶ Public food distribution programme^{19,140} Set up X distribution network⁴⁵ Storage and custody (n = 2) Penalties for unregistered food businesses ⁴⁶ Punishment of free-riders in cooperation ¹¹⁵ Processing (n = 1) Set up X processing factory ⁴⁵

Simulated governance measures, categorized using the approach of Hood and Margretts (2007, p. 21–126)¹¹. Explanations of categories are given in Extended Table 1. X represents any type of livestock, crop or food commodity. N is the number of studies simulating the implementation of each subcategory of governance tool. Governance measures in the first row are targeted towards the wider public. Governance measures in the second and third rows are targeted towards specific group or individuals, respectively. Measures in bold italics are spatially targeted. Subcategories of different governance tools within the main categories nodality, authority, treasure and organization are underlined and bold.

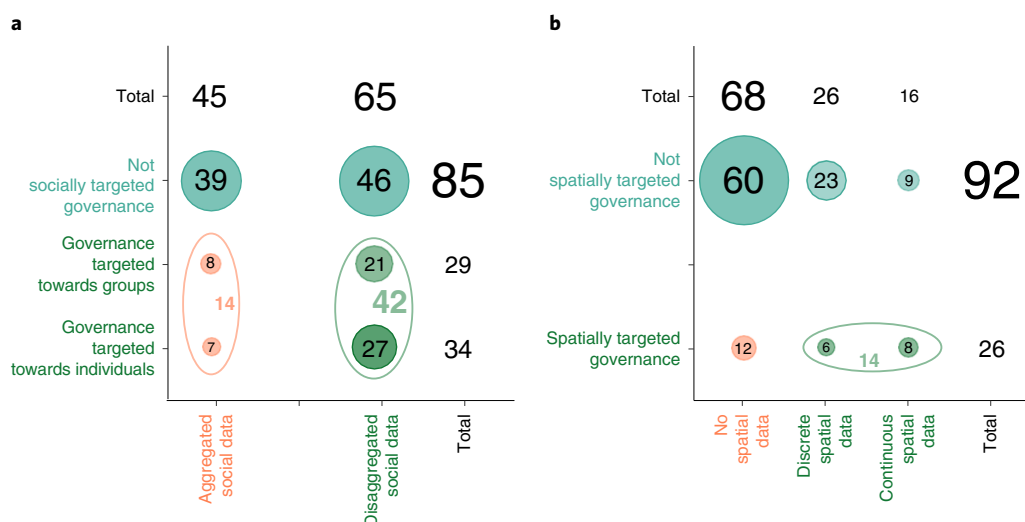


Fig. 4 | Social and spatial targeting of governance measures. a, b, Dark-green bubbles show the number of studies that simulated socially (a) or spatially (b) targeted governance measures with socially (a) or spatially (b) disaggregated data. Turquoise bubbles show the number of studies that simulated untargeted measures with or without socially (a) or spatially (b) disaggregated data. Pink bubbles show the number of studies that simulated socially (a) or spatially (b) targeted governance measures without using socially (a) or spatially (b) disaggregated data. Bubble sizes and numbers are proportional to number of studies.

termed them the ‘missing’³² or ‘hidden’³⁰ middle—except that the ‘productivist paradigm’^{7,33} was less striking. We observed a stronger consumption focus. This may be due to a production bias present in previous reviews⁷, which we also observed when compiling the search string used for this review (Supplementary Note 2). Though not all value chain echelons are relevant for all food systems and commodities, it is important for the field of governance simulation to advance the ability to simulate the role of the missing middle in up- and downstream value chain dynamics. This can be done with any type of simulation model, but requires hardly accessible data on missing middle value chain actors, especially in the Majority World⁹⁷.

Analyses of the quantitative impacts of governance measures on food security are important to inform decision makers about the effectiveness of different governance measures and, through this, speed up the alleviation of food insecurity. To facilitate such analyses, we explored which studies and governance measures within the reviewed pool of literature could be compared as they used the same food security indicators, measured with the same spatial and temporal precision, and were implemented either inside a jurisdiction, outside it or globally. Using these criteria for comparability, we found 26 groups with three to six studies, exploring up to 13 governance measures, that could potentially be compared in meta-analyses. Multiple comparisons could be made between ABM, SDM and optimization modelling studies, SDM and PE modelling studies, or CGE and PE modelling studies. The first group of studies assessed the impacts of nodal, treasure-based and organizational measures on land use and farm income. The second two groups assessed the impacts of treasure-based and authority-based measures on the consumption, import, production and price of cereals. For the full list of comparable simulation studies, their simulated governance measures and their impacts on food security, see Supplementary Dataset 4. Owing to the absence of reporting guidelines within the field, researchers may need to request additional information from the authors of the studies.

We note that our findings are subject to limitations. Firstly, studies were identified using a search string compiled from existing reviews on simulation modelling, governance, food security and food systems. Biases present in these reviews may be only partly

addressed through the compiled search string used in our research. We noticed, for instance, that we initially lacked terms for the consumption echelon, which we therefore supplemented. Other biases may have gone unnoticed. Secondly, we did not include specific governance programmes or food security indicators in our search string. Studies that assess the impact of specific governance measures (for example, the Indian public food distribution programme⁴⁹) on specific food security indicators (for example, dietary income differential⁶⁷) without framing their studies or outcomes in the context of governance and food security might have been overlooked. Thirdly, we did not include grey literature, but the grey literature we did identify did not contain any approaches or topics that were not covered by the peer-reviewed studies (Supplementary Note 2). Lastly, our findings, resulting from a qualitative content analysis, involved interpretation.

Nevertheless, by this systematic review, we connected the fragmented landscapes of studies that simulate food security governance implementation and provided a comprehensive overview of the state of the field, mapping dominant modelling approaches (ABMs, SDMs and CGE models), governance measures (treasure- and authority-based) and value chain echelons (production, trade and consumption). To be able to generate useful knowledge for the community (for example, for meta-analyses similar to those in public health⁹⁸ or ecology⁹⁹), however, future research could benefit from harmonization of food security indicators. We also identified blind spots regarding studies’ choices of governance measures, food security indicators and value chain coverage. We recommend the development of ABMs that simulate the implementation of nodal governance measures (for example, provision of seasonal weather forecasts for farmers¹⁸); socially and spatially disaggregated models that consider socially vulnerable groups and bio-physical heterogeneity and simulate the implementation of socially and spatially targeted governance measures^{21,22,65}; macro-micro coupling or telecoupling to capture potential spill-over effects (for example, trade moratorium on grains from Russia and Ukraine²⁸); and a re-orientation moving beyond availability and access-focused production, trade and consumption studies, towards utilization-, nutrition- and social justice-focused value chain studies.

Methods

Studies sought for review. Food security governance simulation studies sought for this review meet four criteria: they use simulation models (1) to assess the impact of governance measures *ex ante* (2) on food security (3) within a food system context (4). A paper was considered a simulation study if it used a model that simulates alternative scenarios with future projections or alternative (future) realities. Models that simulated alternative historical realities (≤ 1990) and empirical models that assessed the impact of governance that was already implemented were excluded. Additionally, our scope was limited to peer-reviewed English-language journal papers published after 2000. Governance was approached from a tool-kit perspective, looking at the tools that governance entities may use to affect society¹¹. We distinguished four main categories of governance tools: nodality (information dissemination), authority (laws and regulation), treasure (financial incentives) and organization (capacity building, punishment and crisis management)¹¹. Any study that described a governance measure that was described clearly enough to be categorized in this way is eligible for this review (Table 3 and Extended Data Table 1).

With regard to food security, we considered any study that assessed the impact of governance on an indicator for any of the four dimensions of food security: availability, access, utilization or stability (for full list of indicators, see Extended Data Table 1). Indicators related to food safety and overconsumption, though important aspects of the wider field of food governance, were beyond the scope of this review, and have been studied by others^{100–102}. Food systems could potentially encompass all aspects of our lives, but for this review we confined them to the three elements identified by the High-Level Panel of Experts (2017) (ref. 103): (1) food value chains (including food production, storage, distribution, processing, packaging and retail), (2) food environments (the physical, economic, political or socio-cultural context within which people interact with their food) and (3) consumer behaviour. Aquatic food production, consumer behaviour outside of food environments, and hunting, gathering or fishing were beyond the scope of this review.

Search term selection. To identify food security governance simulation studies, we collected search terms from existing systematic literature reviews on the topics of (1) food systems, (2) food security, (3) simulation modelling and (4) governance (for list of reviews, see Supplementary Table 1). Different combinations of search terms were tested on Web of Science and Scopus. For each combination, we went through the first 40 studies. If fewer than two studies were eligible on the basis of abstract and title scanning, the term responsible for those results was dropped (for search terms, see Supplementary Table 2). To test the sensitivity of the selected search terms, the collection of identified studies was compared with the collection of studies identified for the review by Utomo et al.³³. Terms used in studies from their review that met the inclusion criteria of our review were added. The final search string used to identify food security governance simulation studies on 21 April 2021 was:

1. (('food system' OR agricultur* OR farm* OR ((food OR agricultural) AND ('value chain*' OR 'supply chain*' OR value chain* OR supply-chain*)) OR agri-food OR 'food processing' OR 'food production' OR agri-business OR 'food transfer*' OR livestock OR pasture OR 'food consumption' OR 'food purchase') AND
2. (nutrition* OR diet* OR 'food secur*' OR 'food insecure*' OR 'food access*' OR 'food availab*' OR 'food demand' OR 'food supply' OR 'food sovereign*' OR 'food sufficien*' OR 'food insufficien*' OR 'food utili[sz]ation' OR hunger OR malnutrition OR poverty OR livelihood) AND
3. ((agent-based AND model*) OR (multi-agent) OR (individual-based AND model*) OR (simulation AND model*)) AND
4. (govern* OR stewardship OR regime OR politic* OR polic* OR accountabil-ity OR incentiv*)).

Screening process. A total of 1,953 potentially relevant studies were identified through a database search in Scopus and Web of Science (for full list, see Extended Dataset 2). In addition to 624 duplicate studies, a total of 154 studies were excluded before screening as they did not meet the criteria: English-language peer-reviewed journal papers published after 2000 (for screening criteria, see Supplementary Figs 1–5). The remaining 1,175 studies were screened, first on the basis of titles, abstracts and keywords, then, if deemed eligible, on the basis of full text. The first round of screening was performed in Ryyan QCRI, a webtool that helps track and expedite the screening process¹⁰⁴. The second round was performed in ATLAS.ti v9.1.7 (ref. 105). The PRISMA flow diagram (Fig. 1) illustrates the process of the selection of simulation studies for the systematic review.

Data extraction and analysis. Eligible studies were imported to ATLAS.ti for a directed, qualitative content analysis¹⁰⁶ where descriptive codes were used to extract text fragments containing information about the simulation approaches (for the ATLAS.ti project, see Data Repository¹⁰⁷). Coded information relating to characteristics 1–5 is specified in Table 1. The text fragments, along with the descriptive codes attached to them, and meta-data concerning the document they were extracted from, were exported to Excel (for raw data, see Data Repository¹⁰⁷),

then imported to R v4.1.0 for data processing and analysis. For each of the reported results, the number of studies in which (a combination of) codes occurred in was counted. If a study contained multiple code categories per variable (for example, multiple model domains), each code category was counted.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The datasets generated during the current study are available in the FoodSecGovSim2 Code Repository on github (<https://github.com/ateeuw/FoodSecGovSim2>) and on the Data Repository on Dataverse (<https://doi.org/10.7910/DVN/Q9WXC2>)¹⁰⁷. Source data are provided with this paper.

Code availability

The code used to generate the results described in this review can be found in the FoodSecGovSim2 Code Repository on github (<https://github.com/ateeuw/FoodSecGovSim2>).

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Author contributions

Conceptualization: A.S.T., M.A.M. and A.N. Formal analysis: A.S.T. Methodology: A.S.T. and M.A.M. Supervision: M.A.M., Y.D. and A.N. Original draft: A.S.T. Review and editing: A.S.T., M.A.M., Y.D. and A.N.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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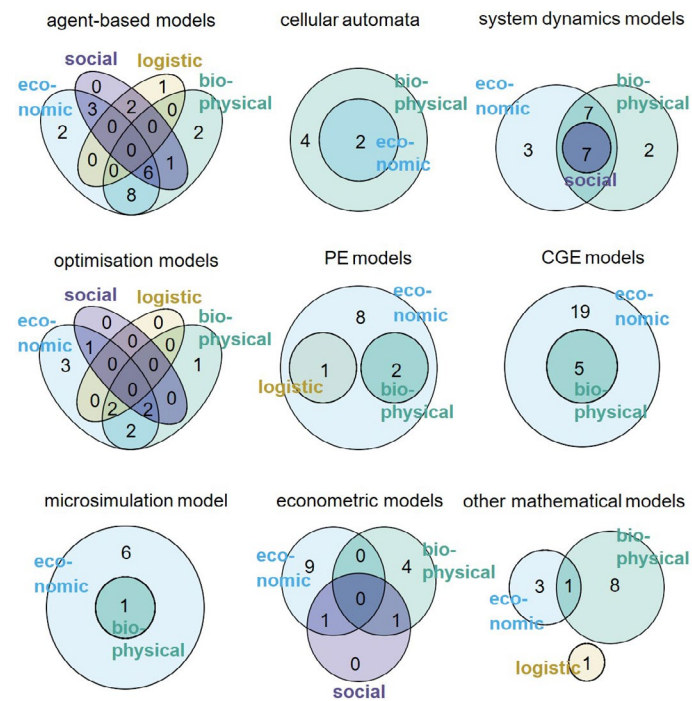
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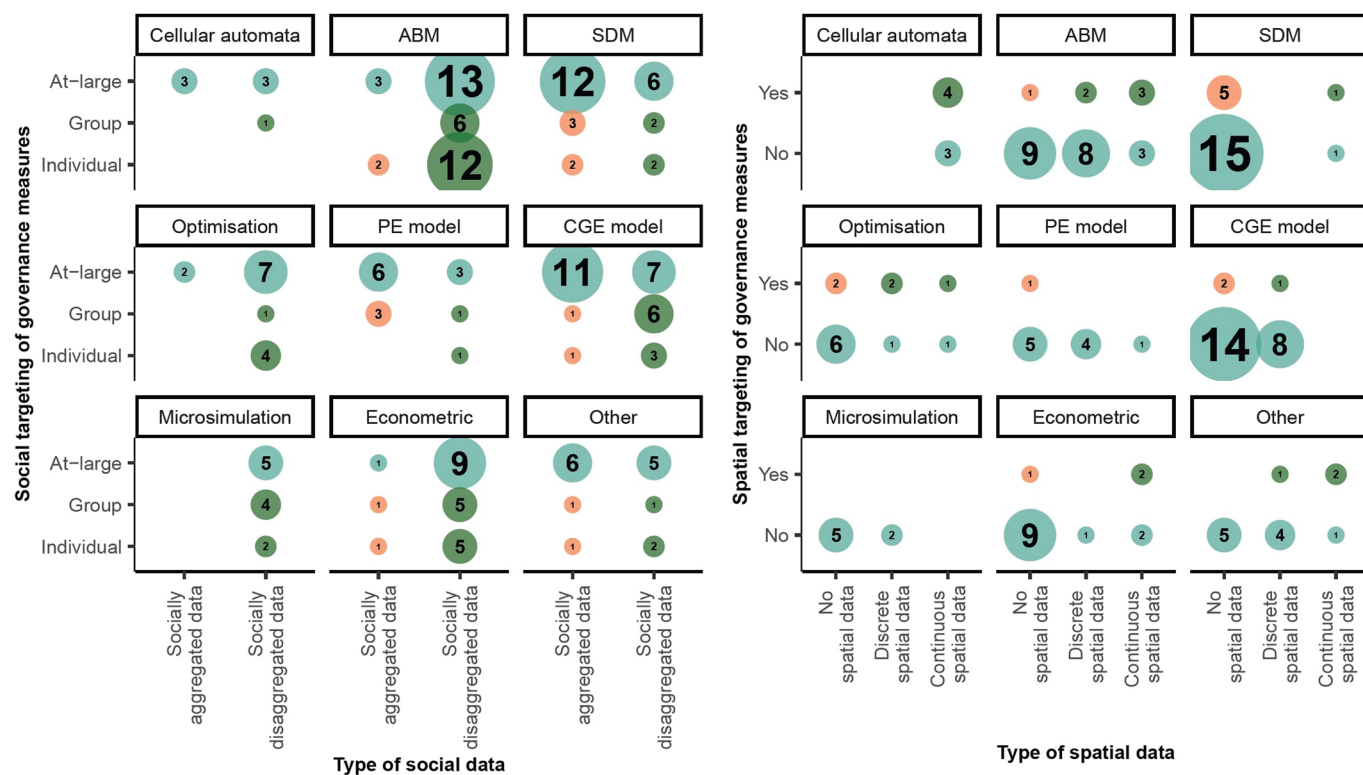
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Extended Data Fig. 1 | Domains of food security governance simulation models.



Extended Data Fig. 2 | Social and spatial targeting of governance measures by different simulation models.

Extended Data Table 1 | Framework and definitions used for governance classification

Characteristics	Nodality	Authority	Treasure	Organisation
Directed towards all	Privished messages ≈ messages that only those with specific skills will find and understand Packaged self-serve messages ≈ messages that only people with specific interest will find Propaganda ≈ messages that are broadcast to the wide public	Open compacts ≈ rights that apply to or can be obtained by anyone Open permits ≈ enablements that can be transferred as gifts or traded Standard constraints ≈ activities that are demanded or prohibited	Bounties ≈ payments made to anyone who produces a certain good or service Bearer-directed payments ≈ payments made to anyone who produces a certain good or service	At-large treatment ≈ planned alteration of the environment in which everyone operates
Directed towards group	Group-targeted messages ≈ messages sent out to groups without being requested	Group targeted constraints ≈ restrictions that apply to a group	Conduits ≈ payments made to a group who then distributes it among their members	Group treatment ≈ planned alteration of the environment in which a group operates
Directed towards individuals	Bespoke messages ≈ tailored messages sent out to individuals without being requested	Certificates ≈ tokens that legitimise the fitness of an individual, document, or product Conditional tokens ≈ tokens that promise or threaten with governance intervention in case something happens Enablements ≈ tokens that allow you to do something otherwise prohibited Directed constraints ≈ tokens that demand or prohibit you from doing something	Contracts ≈ payments made to a specific payee with strings attached Transfers ≈ payments made to a specific payee without strings attached	Processing ≈ of goods, voluntary or involuntary, directly or via privatisation of processing companies Storage and custody ≈ of goods or people, voluntary or involuntary, directly or via privatisation of Transportation and distribution ≈ physical (re)allocation of people or goods, voluntary or involuntary, directly or via privatisation of companies handling it

* Sub-categories of different governance tools within the main categories: Nodality, Authority, Treasure and Organisation, are bold.

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The ATLAS.ti software version 9.1.7 (commercial) was used to collect and extract data from the reviewed studies (as pdf documents). Excel version 2110 (commercial) was used as an intermediate tool to export the data from ATLAS.ti to R as a csv file. The web-tool Rryan QCRI was used to expedite the review process, but this is not required for replication.

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Study description

This study is a systematic literature review that aims to summarize and critically appraise existing food security governance simulation studies by exploring the following research question: How is food security governance simulated? This question is broken down into four sub-questions: (i) Which model types are used? (ii) Which governance measures are simulated, and are simulation models (capable of) assessing socially and spatially targeted governance measures? (iii) How is food security measured, and to what extent are models (capable of) assessing spillover effects? And lastly: (iv) How do simulation studies represent the food system and to what extent are they (capable of) capturing up- and downstream value chain dynamics? It does so by reviewing simulation studies that assess the impact of governance on food security in a food system context. Studies were identified through a systematic database search on Scopus and Web of Science, screened for eligibility, and read. From each modelling study, information on the above-mentioned study characteristics were highlighted and extracted. Then summary statistics, including frequencies and co-occurrence of study characteristics were made and presented.

Research sample

A total of 1,412 unique, potentially relevant studies were identified, and screened for eligibility. A total of 157 studies were excluded prior to screening as they did not meet the criteria: English-language peer-reviewed journal papers published after January 1st 2000. The remaining 1,255 studies were screened, first based on titles, abstracts and keywords, then, if deemed eligible, based on full text. The first round of screening was performed in Ruyan QCRI, a webtool that helps track and expedite the screening process. The second round was performed in ATLAS.ti version 9.1.716. The PRISMA diagram in the submitted manuscript provides the numbers of papers that were rejected and the reasons for rejection in each step of the process, and a full list of all the identified papers and, if applicable, their reasons for ineligibility are provided in the first appendix, submitted along with the manuscript. 110 studies were deemed eligible after full-text screening.

Sampling strategy

To identify food security governance simulation studies, we collected search terms from existing systematic literature reviews on the topics of 1) food systems, 2) food security, 3) simulation modelling, and 4) governance (see Appendix 1 for list of reviews). Different combinations of search terms were tested on Web of Science and Scopus. For each combination, we went through the first 40 studies. If less than 2 studies were eligible based on abstract and title scanning, the term responsible for those results was dropped (see Appendix 1 for list search terms). To test the sensitivity of the selected search terms, the collection of identified studies were compared to the collection of studies identified for the review of Utomo et al. (2018). Terms used in studies from their review that met the inclusion criteria of our review were added. The final search string used to identify food security governance simulation studies on the 21st of April 2021, was: (('food system' OR agricultur* OR farm* OR ((food OR agricultural) AND ('value chain*' OR 'supply chain*' OR value-chain* OR supply-chain*)) OR agri-food OR 'food processing' OR 'food production' OR agri-business OR 'food transfer*' OR livestock OR pasture) AND (nutrition* OR diet* OR 'food secur*' OR 'food insecur*' OR 'food access*' OR 'food availab*' OR 'food demand' OR 'food supply' OR 'food sovereign*' OR 'food sufficien*' OR 'food insufficien*' OR 'food utili[sz]ation' OR hunger OR malnutrition OR poverty OR livelihood) AND ((agent-based AND model*) OR (multi-agent) OR (individual-based AND model*) OR (simulation AND model*)) AND (govern* OR stewardship OR regime OR politic* OR polic* OR accountability OR incentiv*)).

Data collection

Eligible studies were imported to ATLAS.ti for a directed, qualitative content analysis where descriptive codes were used to extract text fragments containing information about the simulation approaches. Coded information included:

- Meta-information: Title, authors, publication year, and journal
- Simulation methods: Simulation model types and domains, aims, empirical foundations, simulation of feedbacks, and whether sensitivity analyses and validation were performed
- Food value chain: The food system context within which the governance measures were implemented (broken down to specific food supply chain echelons), the food commodities of interest, and value chain agents included in the models
- Governance measures: Simulated governance measures, classified according to Hood & Margretts (2007), nature of the governing entity (public, private or communal), whether an effect- or process-based simulation approach was used, whether the measures were spatially targeted, and the objectives and assessment indicators of the governance measures
- Spatio-temporal specificity and geographic focus: The spatial scale and spatio-temporal extent and resolution of the model, and the geographic focus area.

The text fragments, along with the descriptive codes attached to them, and meta-data concerning the document they were extracted from, were exported to Excel, then imported to R version 4.1.0 for data processing and analysis.

Timing

In this review, we assessed studies that were published between the first of January 2000 and the 21st of April 2021.

Data exclusions

As described in the research sample section, only English-language peer-reviewed journal papers published after 2000 were considered in this review. 157 studies were excluded prior to screening because they were published prior to the first of January 2000 (n = 85), conference proceedings (n = 60), book chapters (n = 6), written in another language than English (n = 5), or retracted after having been published (n = 1). During screening, studies were excluded if they were found not to be simulation studies, not to assess the impact of a governance measure that was aimed at improving food security, did not use any food (in)security proxies or indicators to assess the impact of governance, or did not simulate the implementation of governance in a food system context. The

PRISMA diagram in the submitted manuscript provides the numbers of papers that were rejected and the reasons for rejection in each step of the process, and a full list of all the identified papers and, if applicable, their reasons for ineligibility are provided in the first appendix, submitted along with the manuscript. 110 studies were deemed eligible after full-text screening.

Non-participation

3 studies deemed to potentially be eligible based on title, keywords and abstract screening could not be retrieved via their respective journals or upon request via the corresponding author.

Randomization

No experiments were conducted in this research and thus needed no randomisation was required.

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