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DARTS: Modelling effects of shocks on global, regional, urban and rural food security

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Abstract

Food trade networks represent a complex system where food is periodically produced in different regions of the world. Food is continuously stocked and traded. Food security in a globalised world is vulnerable to shocks. We present DARTS, a new agent based model that models monthly dynamics of food production, trade, stocking, consumption and food security for different interconnected world regions and a city state. Agents in different regions differ in their harvest seasons, wealth (rich and poor), degree of urbanisation and connection to domestic and global markets. DARTS was specifically designed to model direct and indirect effects of shocks in the food system. We introduce a new typology of 6 distinct shock types and analyse their impact on food security, modelling local and global effects and short term and longer term effects. A second important scientific novelty of the model is that DARTS can also model indirect effects of shocks (cascading in space and in time, lag effects due to trade and food stock buffering). A third important scientific novelty of the model is its' capability of modelling food security at different scales, in which the rural/urban divide and differences in (intra-annually varying) production and trade connections play a key role. At the time of writing DARTS is yet insufficiently parameterised for accurate prediction for real world regions and cities. Simulations for a hypothetical in silico world with 3 regions and a city state show that DARTS can reproduce rich and complex dynamics with analogues in the real world. The scientific interest is more on deepening insight in process dynamics and chains of events that lead to ultimate shock effects on food security.

Author summary

Shocks like crop failure, cash loss (e.g. due to pandemic, war, financial crisis), hoarding and various types of trade shocks can cause hunger. Different groups (rich/poor, rural/urban) in different regions of the world (e.g. North/South, equatorial, city state) have different vulnerabilities. In a globalised world with continuous food trade within and between regions and with people's differences in trade network connections and purchasing power, it is hard to understand the where, when and why of shock impact on different groups. Shock effects can be exported from one region to the other. Food stocks act as a buffer and more rapid depletion of food stocks due to a shock can cause delayed impact

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several months after a shock occurred. Shocks can be absorbed if food stocks are timely replenished. DARTS is a new agent-based model of local to global food supply chains (production, trade, consumption). DARTS was specifically developed to allow for modelling effects of shocks. A simulation example is presented for an imaginary world to which a range of shocks is applied and their impact and impact pathways is analysed. The simulation examples illustrate how a model like DARTS can help understand the dynamics of shock impacts. As a more stylised or conceptual model DARTS is designed less for accurate prediction and more for gaining insight in the mechanisms from a shock at one place and time to its ultimate effect on food security.

1. Introduction

Global food security threatened by both short-term events (shocks) and long-term trends (stresses) and their interactions [1]. Examples of stresses are exhaustion of natural resources, climate change, population growth and diet shift towards more energy and nutrient-rich diets [1–4]. Examples of shocks are more immediate events, such as drought, floods, pandemics, financial crisis and civil war. This paper introduces a classification scheme of these shocks resulting in 6 distinct categories (Fig 1, Table 1). For instance, floods, landslides and droughts all lead to local crop failures, whereas the COVID-19 pandemic threatened livelihoods and thereby represented a cash shock. These six categories therefore affect the first 2 pillars of food security, availability and accessibility, in different ways, with as the ultimate consequence hunger. This paper explores the impact of these shock categories on simulated food systems with complex network structure.

As the world food system has become more globalised and integrated, shock types other than the usual suspect (crop failure) have become more prominent causes of hunger. Sen [5] in an analysis of 5 recent famines showed hoarding, large drops in cash assets and trade shocks as prominent causes of famine, while crop failures played only a minor role. Ó Gráda [6] analysed causes of two centuries of famines, which include crop failures, war and policy failures.

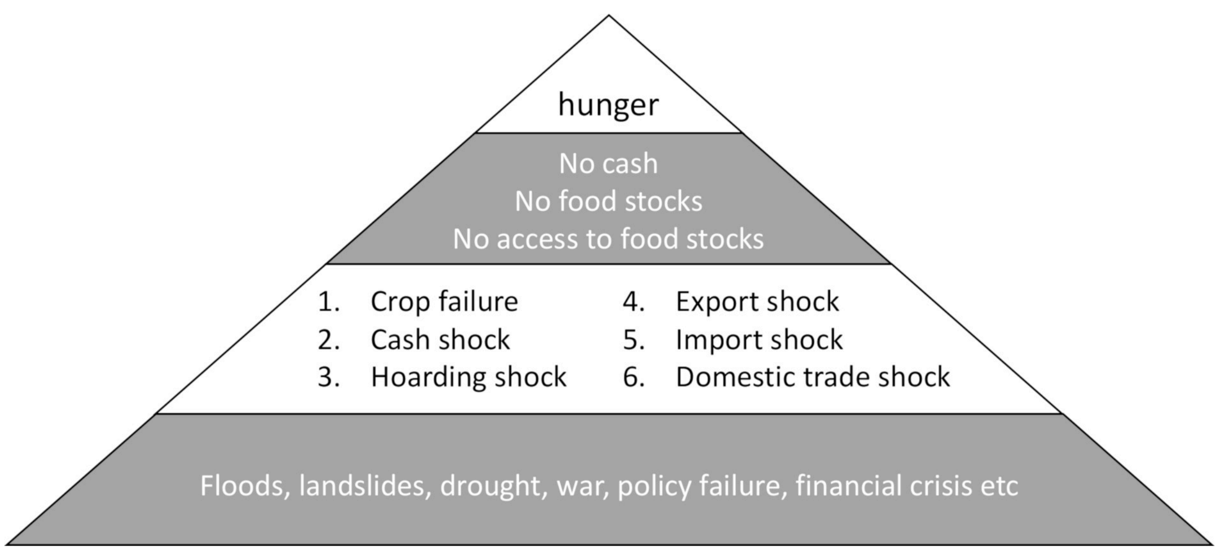

Fig 1. Hierarchy of causes of hunger.

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Table 1. Six shock types.

Shock type	Definition	Cause (examples)	Consequences
1. Crop failure	Crop failure	Drought, Flood, Locusts, etc	Delayed impact because Trader's stocks are depleted more rapidly than normal. Impact less for wealthy agents with access to other markets.
2. Cash shock	Consumers loose cash	Civil war; Financial crisis	If too large, immediate impact of not being able to afford food. Possibly positive effect for regions not affected, if international market is depleted less rapidly than normal.
3. Hoarding shock	Consumers are hoarding = buy	Panic about (anticipated) shortages. Self-reinforcing.	Some consumers having more than they need. Less food available for non-hoarding consumers
4. Export shock (F2TI)	Industrial Farmers cannot sell to international Traders	Policy decision (e.g. response to crop failure). Harbors locked down due to war.	Cascading effects especially for import dependent regions. Region itself possibly also affected if regional traders lack cash or storage capacity
5. Import shock (TI2C)	Consumers cannot buy from international. Traders	Cyber-attack. Harbors locked down due to war.	Especially urban consumers with few trade connections affected. Urban poor in the city state if relying completely on international market
6. Domestic trade shock (TR2C)	Consumers cannot buy from regional Traders	Earthquake, Tsunami destroys domestic infrastructure.	Especially rural consumers affected. Urban consumers affected only at moments when international stocks are at same time also low.

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Fig 1 suggests a causal chain of events from war to cash shock to reduced food accessibility to hunger. Market integration and globalisation contribute both positively and negatively on local food security. Being able to source food from distant regions mitigates against local production shocks, whereas the same market integration can import distant food shocks such as when an import dependent region is affected by an export ban from another region. The resulting dynamics, which are complex and include the effects of food stocks and trade are currently poorly understood.

The complexity of the global food system and the resulting challenges for understanding and modelling these systems is widely recognised [1]. Self-sufficiency differs between regions [7–10] and for import-dependent countries, international food stock availability and purchasing power [1,8,10–13]. Moreover, food stocks (reserves) fluctuate on a global [14] and local scale [15], whereas physical access to markets also varies significantly both internationally and between rural and urban areas within countries [16]. Global trade increases food security through imports when domestic reserves are low, but also causes spill-over effects where crop failure or export bans in one region cause shortages in other regions [1,8,10–13]. An illustrative example of such spill-over effects is the Asian rice price crisis, in which hoarding in Asian countries [17–19] caused food riots in African cities [17,20].

Shocks, by their very nature, drive the food system out of equilibrium, which complicates their analysis by standard "General Equilibrium Model" (GEM) models [21,22]. Agent-based models (ABM) can dynamically simulate production, trade and consumption [23–28], without making many of the assumptions necessary for GEM and are therefore better positioned to simulate shocks in complex food systems. ABM's allow for analysing what happens from the moment after a shock, immediately and several months after, until possibly reaching a new equilibrium [29]. Previous studies on shock propagation through food trade networks were limited to modelling just 1 or 2 shock types [8,11,13,23, 30]. Here we present a new analysis with the DARTS ABM model that allows for modelling all 6 shock types listed in Fig 1. The current paper builds on an earlier DARTS paper [13] which focussed on analysing effects of urbanisation and globalisation of trade on food security and which considered only 1 shock type. Here in this second DARTS paper we model 6 distinct shock types applied in a modern world with greater inequality between regions in terms of production and wealth. Compared with the earlier paper we here present a more in depth analysis of cascading of shock effects in space and in time.

Most food security research focuses either on effects of shocks on the household/village scale [15,24,25,31–33] or on the national/international scale [8,11,28,34,35]. This ignores the interconnectedness of scales through trade networks which leads to cascading effects between and within scales. The role of trade networks and differences in market connections is often poorly elaborated, or when modelled they are modelled only between and not within countries [27,28,36]. Many empirical modelling studies on food security are, constrained by data availability at annual time scale, confined to the annual time scale. But food availability at local, national and international scale fluctuates within the year [30] due to climate driven monthly harvest patterns [37], which lead to a build-up of food stocks during the harvest season and gradual depletion of food stocks thereafter. Many food security studies ignore the buffering effects of food stocks or food reserves. The single study we know of that does jointly consider effects of reserves and trade on exposure to food supply shocks is again limited by its annual time scale [12]. We might understand this general neglect of the role of food stocks from a general lack of data. But lack of data should not be confused with lack of importance. Seminal work by Sen [5] did show the importance of food stock dynamics and showed that it is possible to estimate monthly food stock dynamics from production, trade and consumption data.

Rather than restricting ourselves by data availability, as many previous empirical studies have done, we here propose a novel hypothetical approach that focusses more on developing new modelling capability, which can be extended later on by parameterisation for specific cases. Novelty of the proposed model here are: (1) the monthly time scale which is important because of intra-annual variation in food availability, (2) explicitly modelling of food stocks held by farmers and traders, (3) explicitly modelling separately food security for the rural and urban areas and differences between the rich and the poor, (4) modelling both domestic and international trade and (5) modelling a larger number of shock types than what was done in previous studies. These novelties allow for modelling model shock effects on food security across scales, cascading between regions and within regions between rural and urban areas and cascading in time (immediate and delayed effects).

The aim of the current paper is to contribute a deeper understanding the complex food system and its sensitivity to shocks, by simulating in an in-silico world the effects of the 6 shock types (Fig 1) and presenting an in depth analysis of how, where and when these shocks impact food security. The contribution of this paper is more conceptual, showing the capability of agent based model of simulating effects of shocks. In its current state of model development, DARTS' predictive capacity for real world countries and cities is limited due to lack of parameterisation for specific countries and cities–we reflect on this in the discussion.

2. Results

We defined an in-silico world (§4.2) in which we modelled food trade with and without a range of shocks. Food stock dynamics, by whom they are held and through which trade connections they are accessible are key to understanding whether agents in the in silico world have access to sufficient food. Therefore, this section first discusses stock dynamics without shocks (§2.1.1), followed by an in depth analysis of stock dynamics and impact on food security in two shock scenarios (§2.1.2 and §2.1.3). Special interest is given to complex emerging dynamics, including spatial and temporal cascading of shock effects that emerge from how shocks affect food stock dynamics in the in-silico world. In section §2.2 we present and discuss simulated impact of all shock types on different regions and groups of agents, in the short run of up to 3 months immediately after a shock and averaged over in the longer 12 months after the shock. In section §2.3 we discuss shocks cascading from international market to rural community.

2.1 Food stock dynamics

2.1.1 Food security in the in silico world without shocks. The first part of Fig 2 (left of the vertical black line) shows an example of Traders' stock dynamics without shocks. International stocks (dashed brown) accumulate in August and September, coinciding with the harvest season of the main exporting region North. From October to April international food stocks decrease more rapidly than domestic food stocks in North and Middle due to urban consumers' preference for purchasing internationally (§4.1.2). In this in silico world, June (years 6.5, 7.5 and 8.5) is a critical month for all regions, as at the end of this month both international food stocks and domestic food stocks are completely depleted.

Domestic stocks in regions Middle and North are not yet completely depleted in May (year 7.4) and the harvests in North already start in June. Thus in June some food is available, which is all immediately consumed leading to zero food stocks end of June. Whether enough was available for all consumers during that critical month June is seen in the food satisfaction indices, which show sufficient food availability for most of the wealthy and insufficient for the poorest faction of world population (supporting material S2 Fig, panel 0), thus annual recurring hunger for the poorest, sometimes also referred to as the "hunger month(s)".

Fig 2 shows domestic food stocks in South (net importer) are completely depleted in the period from July to December and that during this period South is strongly dependent on the international market. During this period the rural community (not connected to the international market) suffers from periodic food shortages. This is reflected in low 3-month average satisfaction for the rural South from June to August (supporting material S2 Fig, panel 0) and

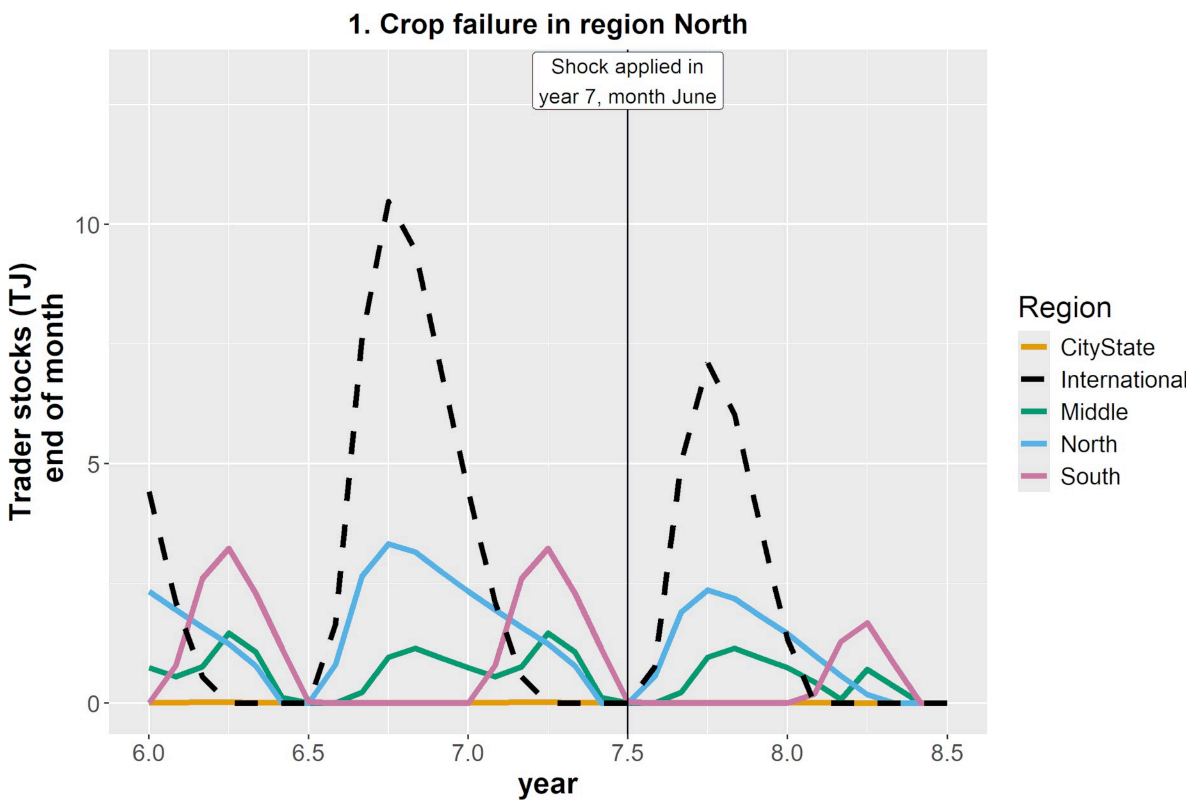

Fig 2. Simulated Trader stock dynamics in the Crop failure in region North scenario. Left of the vertical line shows baseline stock dynamics (without shocks), right shows stocks during and after a shock.

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is reflected in low annual average satisfaction for the rural South (S3 Fig panel 0). Regional annual average satisfaction in the South is nevertheless relatively high (S3 Fig, panel 0: 0.884) because domestic shortages occur only half of the year and affect only the rural South.

2.1.2 Export shock can lead to food "locked" in farm storage. A counterintuitive simulation outcome is the export shock in North causing increasing hunger in North. One would expect an export shock to cause more abundant food availability in the domestic market. Recall industrial farmers preferably sell to the international market (§4.1.2). Due to the export shock industrial farmers will seek to sell their product to regional traders. The ability of regional traders to absorb extra food supply then becomes critical. If regional traders momentarily cannot absorb the extra supply from industrial farmers because they just spent all their money and regional storage facilities are already completely stocked because all farmers are offering their products in the same main harvest period, then food remains in store at the industrial farmers. Such dynamics are present in our simulations (Fig 3). The export shock lead to an increase in Consumer-Producer stocks (in this case the industrial farmers) and did not lead (as one would hope) to an increase in regional Traders' stocks. In this scenario, there is sufficient food present in the region but food is with Farmers rather than Traders, which makes it unavailable for Consumers who can only buy from traders, leading to hunger for the Consumers despite food present in the same region. An illustrative historical example of joint occurrence of hunger and food "locked" in farm storage is the Dutch hunger winter of 1944/1945, where farmers had harvested their crop in autumn 1944, but due to confiscation of fuel and means of transport and due to railway strikes, there were great problems getting food from the Dutch farms to the starving population in the cities [38].

2.1.3 Spatial and temporal cascading effects of crop failure in North. A crop failure in North leads to a reduced peak in international food stocks (Fig 2 black dashed line to right of the vertical line = after the shock). This causes Northern urban consumers to buy more from

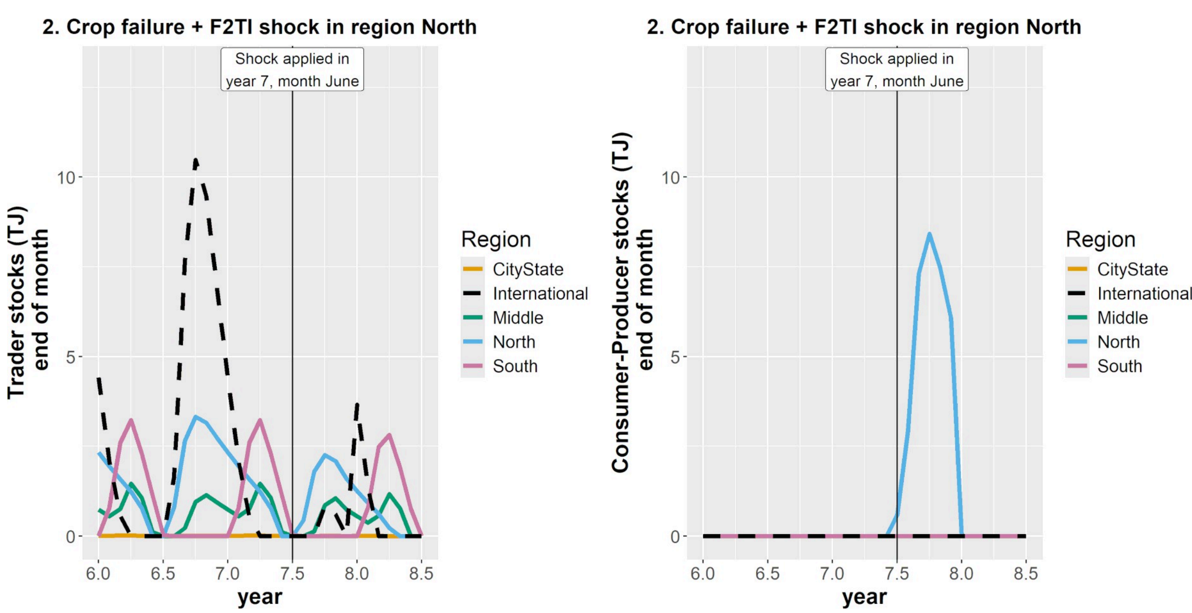

Fig 3. Simulated Trader and Consumer-Producer stock dynamics in the Crop failure + Export shock in region North scenario. Left of the vertical line shows baseline stock dynamics (without shocks), right shows stocks during and after a shock. Right panel shows Consumer-Producers normally do not stock, but due to a combination of export ban and capacity problems of Northern regional traders, food stocks remain with the Northern Industrial farmers, food which is then not accessible to other Northern Consumers who can only buy from traders.

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the domestic market in July (year 7.6), which in turn leads to a lower peak and earlier than normal depletion of domestic stocks in the North (blue line). Ultimately, this leads to hunger in region North 12 months after the shock (year 8.5, June). Averaged out over a period of 12 months, this delayed impact shows in Fig 4B as a small negative impact for Northern food satisfaction. A second effect of the Northern crop failure, also mediated by more rapid international food stock depletion, is that it forces the Southern urban population to buy from the domestic market earlier than normal (February in year 8). This leads to more rapid depletion of Southern domestic stocks (Fig 2, reddish purple line), leading to hunger in the South 12 months after the shock. The effect on South is seen in Fig 4B as a small negative impact for Southern food satisfaction. This detailed analysis thus shows cascading effects in time (delayed effect, in North and in South) and in space (spill-over from shock in North to impact in region South).

2.2 Impact of shocks

Supporting material shows consumption satisfaction in the baseline (no shock) scenario and in the various shock scenarios, for shocks applied in region North (S2 Fig, S3 Fig) and shocks applied in region Middle (S4 Fig, S5 Fig). Spider diagrams presented here show the change in food security compared to the baseline.

2.2.1 Vulnerability of regions. Fig 4 shows the impact of shocks applied in regions Middle and North on all 4 regions of the world. Greater effects are seen in Middle and North (where we applied shocks). The City State is almost invulnerable to shocks, while the South is negatively affected by export shocks in North and by hoarding. This comparison shows being poor and not self-sufficient is a dangerous combination and suggests city states will only be safe in terms of food security if they are sufficiently rich.

Positive spill-over effects of North/Middle shocks on food consumption on region South were also witnessed from simulation outcomes and cannot well be visualised in Fig 4. We found food consumption in South increased when cash or import shocks occurred in region North and Middle. Both these shocks led to a less rapid depletion of international stocks by

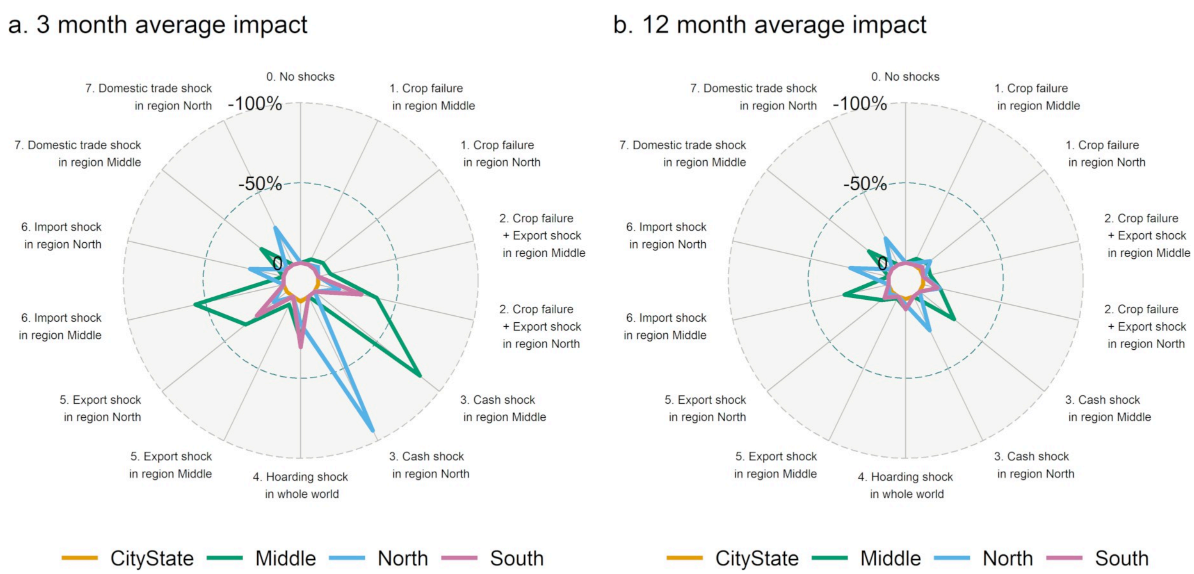

Fig 4. Regional impact of simulated shocks on a 3 and 12 month timescale. Numbers show change in food satisfaction compared with baseline (no shock) food satisfaction. Panels: (a) 3 month average impact; (b) 12 month average impact.

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consumers in North and Middle, and thereby an increased availability for the South in the critical month June. This positive effect can be seen in S2 Fig: consumption satisfaction of the South is 0.823 (S2 Fig panel 0, without shock) and this number increases to 0.966 in S2 Fig panel 3 (cash shock in region North) and 0.966 in S2 Fig panel 6 (North cannot import from international traders).

Annual averaging out (Fig 4B) can be useful as a first step towards identifying region vulnerability to particular shocks but must be followed up by closely zooming in on months (e.g. Fig 4A), to identify when impact is large. As we showed, large impact can be caused

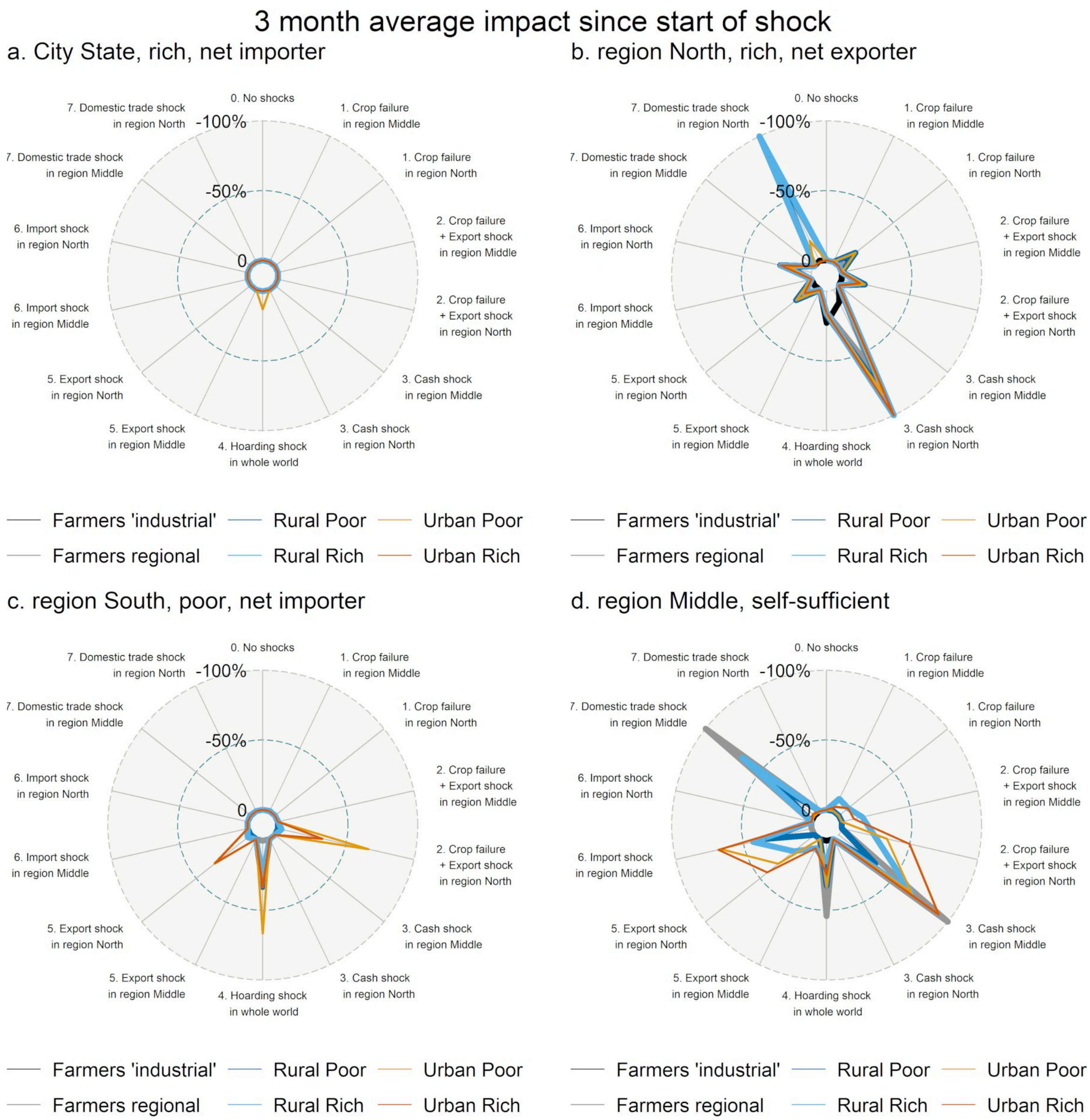

Fig 5. Regional immediate impact of simulated shocks per region and per group of agents. Numbers show change in food satisfaction compared with baseline (no shock) food satisfaction. Panels: (a) City state; (b) region North; (c) region South; (d) region Middle. Differences in line thickness are purely for aesthetic reasons, for visualising overlapping lines. For aesthetic reasons the same legend is shown for all regions, while the City State has no industrial farmers and no rural agents and the region South has no industrial farmers in the in-silico world simulated here.

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immediately after a shock, but also a number months after the shock in case of food stocks buffering against immediate negative effects. Investigating in intra-annual food stock dynamics, domestic and international (§2.1) can help understand the causal chain of events from a shock in one region and at one point in time to its' ultimate impacts.

2.2.2 Vulnerability of agent types within regions. Vulnerability of agent types differs strongly between regions and between urban and rural population within each region (Fig 5). For the urban population vulnerability depends on food stock availability in the international and domestic market. As long as international stocks are available, urban consumers in one

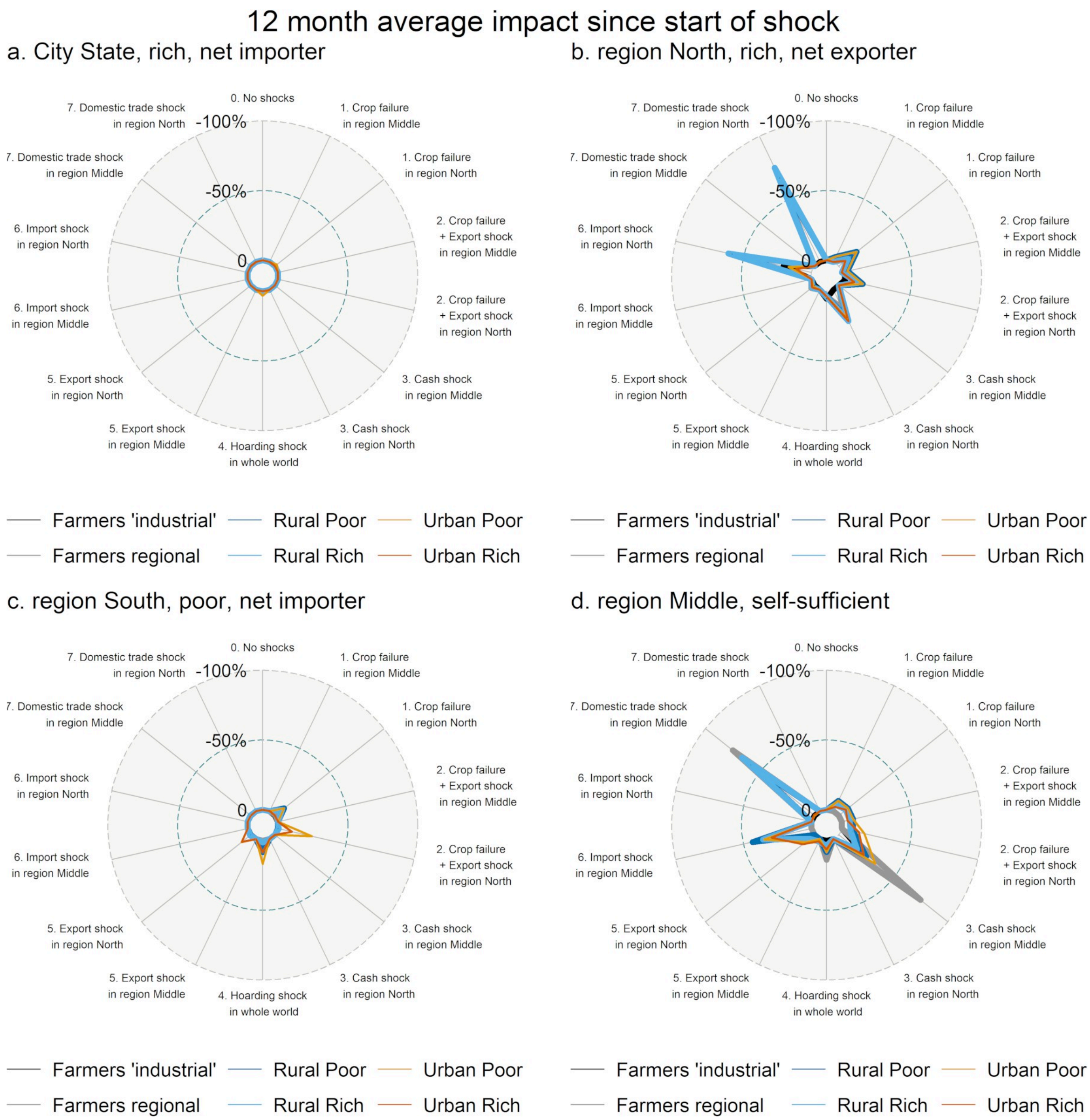

Fig 6. Regional annual impact of simulated shocks per region and per group of agents. Numbers show change in food satisfaction compared with baseline (no shock) food satisfaction. Panels: (a) City state; (b) region North; (c) region South; (d) region Middle. Differences in line thickness are purely for aesthetic reasons, for visualising overlapping lines. For aesthetic reasons the same legend is shown for all regions, while the City State has no industrial farmers and no rural agents and the region South has no industrial farmers in the in-silico world simulated here.

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region are in competition with urban consumers around the world. In this international market, urban wealthy in South are last in cue after the (wealthier) urban wealthy in the other 3 regions, which makes the urban South relatively more vulnerable to shocks in the international market (and the City State urban wealthy least vulnerable). The situation changes when international food stocks are depleted. The urban wealthy in South then revert to the domestic market where they are first in cue (being richer than the Southern urban poor and rural poor). Furthermore, wealth matters in times of insufficient food availability, but wealth has no impact on food security in times with ample food available and wealth has no impact on food security in times with no food available at all.

Modelling the food security of farmers remains a challenge. Contrary to the non-farmers, farmers have an irregular income, with a peak in income after harvest. DARTS has a parameter for how much of their income from farm production farmers keep as savings. The remainder is spent as non-food spending. In reality, farmers often use this periodic farm income to repay loans, buy farm inputs for the next season and pay off other large investments. Earlier simulations indicated that how much of their income from food sales after harvest they set aside as savings significantly affects their food security later in the year.

Fig 5 shows immediate (3 months after) effects of shocks on agent types within regions. The most striking feature that two shocks (cash shock and domestic trade shock) have a very strong local negative effect. A cash shock affects the entire population, whereas a domestic trade shock affects only the rural population. The impact of a domestic trade shock is very large (Fig 5) on a small (rural) faction of the population (§4.2: only 28% of the population is rural). Recovery from the cash shock is relatively fast, which results in a similar impact of these two shocks on a regionally annually averaged time scale to (Fig 4B).

2.3 Shocks cascading from international market to rural community

Fig 6 shows a counterintuitive effect of rural populations in Middle and North being negatively affected by import shocks (i.e. where the urban community in these regions cannot import from the international market). In DARTS rural agents cannot buy from the international market because rural agents are only linked to domestic traders. How and why then is the rural population affected by this shock in the international market? We retraced the causal chain of events though closer scrutiny of food stock dynamics. The urban population normally preferentially buys internationally (§4.1.2). During an import shock the affected urban community buys (more than they would normally do) from regional (domestic) traders. This leads to a more rapid depletion of domestic stocks. After the import shock is over the urban population returns to buying from international traders, while the rural population is left with regional stocks that have been depleted more rapidly than normal. In contrast to previous sections §2.1.2 and §2.1.3 which showed cascading effects *between* regions (shock in North impacts on South), this section shows that, even though the rural consumers are not directly connected to the international market, they can still be affected by shocks in the international market, an indirect affect caused by the urban population that buys its food from both the international and the domestic market. Incidentally notice through the same dynamics an import shock in North (i.e. North can temporarily import less from international market) can also affect the rural population in region South: if due to import problems in North more food remains for sale in the international market this could lead to the urban South buying more from the international market, leading to less rapid depletion of Southern domestic food stocks and therefore more food available for the rural South. Such positive effects can be read from Supporting Material S2 Fig, where food satisfaction of the rural South increases from 0.333–0.385 (S2 Fig panel 0, no shock) to 0.688–0.967 (S2 Fig panel 6, north cannot import).

3. Discussion

3.1 Main findings

DARTS was designed specifically to investigate how shocks affect global food security in a complex world where food security depends not only on production but also on wealth, food stocks and trade connections, which are distinctly different between cities and rural areas. This paper extended the DARTS model [13] by including 6 shock types: crop failure, cash shock, hoarding shock and three types of trade shocks. Simulations showed that DARTS can reproduce rich and complex dynamics with analogues in the real world, including immediate and/or delayed effects, spill-over effects between regions and spill-over effects within regions between urban and rural communities.

We observed shock impacts with straightforward explanations, but also several unexpected outcomes that nevertheless are consistent with the rationale and design of the model. These unexpected outcomes highlight the usefulness of DARTS: close analyses of the causal chain of events helped deepening our understanding of the complexity of shock effects in a globalised food trade network. DARTS was deliberately designed as a highly abstract and simplified representation of food systems, with maximum scope for manipulation and deeper investigation of the emergent behaviour in response to shocks. In its choice to favour abstraction above realism, it resembles the Sugarscape model [39] a seminal ABM showing how a minimal set of assumptions leads to important 'stylised facts' of social systems, such as unequal wealth distributions. DARTS is also akin to more conceptual approaches to modelling global food trade networks [28,30], which like DARTS model food flows between different parts of the world including Northern and Southern hemisphere regions. Compared with these earlier network studies, scientific novelties of DARTS are its explicit modelling of differences in trade relations of rural and urban agents, the simulation of intra-annual (monthly) food stock dynamics and simulation of a larger number of shock types. The importance of explicitly modelling trade relations and differences between cities and rural areas has been stressed in earlier studies [30]; the current study is to our best knowledge among the first to explicitly model these urban/rural trade differences in the context of food security modelling. For example consider the shocks cascading from international market to rural community. Existing agent based models developed for rural communities [23,24,31] have to date been limited in their capability of modelling such indirect shock effects from international market to rural communities. The DARTS model and the shock scenario analysis presented here show that such effects can occur and presents a novel way of modelling such effects of shocks cascading from international market to rural community. It shows food purchasing choices of the urban population are the key mediating factor determining how external shocks propagate to impacts on the rural population.

As this paper and earlier works [28,30,40] showed, food security depends on complex combinations of timing of harvests, food stock dynamics, wealth, food losses, trade connections. Modelling forces us to be explicit to about assumptions and allows us to quantitatively simulate effects of shocks under assumptions made on model parameters and network topology.

3.2 Validation

DARTS is designed as a stylised representation of the world food system and therefore precludes explicit comparisons with real-world food system dynamics. However, even if DARTS would resemble the real world more closely, e.g. if parameterised for specific countries as in [8,11,12,14,28], any validation would still only be possible at the country and annual scale, because that is the scale at which international organisations such as the Food and Agriculture

Organisation (FAO) and World Bank (WB) collect their data. Very different rural-urban intra annual dynamics could, when aggregated to the national and annual scale, produce the same outcomes at this national and annual scale. Thus it still would be impossible to tell from such aggregated validation whether intra-annual dynamics and differences between rural and urban areas are accurately simulated, or just an artefact of cancelling out of intra-annual over- and underestimations of simulated variables. Rather than embarking on such validation exercises, one could also conclude there is a need for expanding current data collection procedures. Supporting material shows potential sources of real-world data for parameter estimation (S1, S2 and S3 Table) and validation (S4 Table) and it shows gaps in current public domain data sources.

Effects of shocks in food trade networks have been investigated before, but have been confined to trade between countries, not drilling deeper down to effects within various supply chains through which food flows from producers through traders to consumers [27,36]. While we know about the importance of trade, very limited data are available at the scale modelled by DARTS, while as we showed here, differences in trade connections and intra-annual fluctuations in food stock reserves held by different traders (and farmers) have big impact on monthly food security. One could say much of the current modelling work [8,11,12,14,28] takes data availability (country, annual) as a starting point and designs models from there, whereas here we have reversed the model designing process. We started of designing a model based on known factors important for food security [5,6], showed a model like DARTS can help deepen our understanding of food security and identified from this modelling exercise gaps in existing global data availability. The work presented here shows the importance of refining and elaborating our data collection, specifically in the domains of collecting more data on trade and on food stocks at a monthly time scale, and differentiation of food supply and demand between urban and rural areas. The promise held by a model like DARTS is that, once more of such data become available, they can be integrated in DARTS and predictive capacity can be tested and improved. Until then, the value of the model is more in the domain of research, becoming a useful tool for helping to understand dynamics and factors to consider in food security research.

3.3 Behaviour

We consider DARTS and the set of 6 shock types as a first step towards a better understanding of the resilience of the global food system. Elaboration of the shock types and of the model is possible and desirable. Parameterisation for countries and specific commodities (e.g. rice) is desirable and possible to a certain extent (see the discussion in previous section). One element that deserves special attention is increasing the realism and complexity of agent behaviour in the model. Currently, DARTS agents exhibit no adaptive capacity to shocks or recurring periodic hunger. A common behavioural adaptation to recurring periodic hunger is to switch to an overall lower food intake throughout the year: chronic malnutrition rather than starving [41]. This adaption helps to avoid completely running out of food at the end of the year. Admittedly this is not an ideal adaptation and preferably absolute food availability would be increased. We showed in section 2.1.3 increased hunger in North due to a 12 months earlier crop failure. This impact in North occurred in a context of Northern industrial farmers continuing exports. A logical adaptation would be for Northern industrial farmers to temporarily sell more to the domestic market, or for regional traders to buy from international traders at times when domestic demand exceeds supply. The simulations show the consequences of an export ban without alongside increase in capacity of the domestic trade sector for absorbing increased domestic supply. Comparing simulations without (this paper) and with a certain behavioural adaptations can help in a priori assessment of effectiveness of behaviour to reduce shock impact.

DARTS currently does not include any type of safety net, whereas cash and food relief are widespread in the real world and are normally increased in response to shocks. A model like DARTS allows for in silico thought experiments, simulating the potential impacts of behavioural adaptations such as safety nets. We can theoretically deduct that in cases of ample food availability relief against cash shocks can help increase overall food security. But if overall food availability is not enough to feed the world at a particular month, then increasing purchasing power of one group will inevitably reduce hunger for that group while increasing hunger for the other groups with less purchasing power. The question arises whether food trade and consumption such as simulated with DARTS is essentially a zero-sum game with net zero improvement in global food security. DARTS shows food trade is not always a zero-sum game. There can actually be an improvement in overall food security if the situation is one of hunger in one part of the world while ample food is available in other parts of the world. It is the complex dynamics of food trade and food stocking, which depends in turn on production volumes and timing and on trade connections, that determines whether genuine net improvements in global food security are possible. Interventions more likely to have net positive effect are those reducing food stock losses. Reductions in stock losses can be achieved by lowering the monthly fraction food stock losses (a model parameter) and faster turnover of food stocks [13].

Farmers' (behavioural) response to shocks is not yet included in DARTS. Farmers often do respond with one cropping season delay to shocks: food shortages lead to increasing farmgate prices, which allow for farmers to buy and apply more inputs and achieve higher yields the next season. In conjunction, governments, can (but do not always) increase investing in their agricultural sector after periodic and incidental shock-induced food insecurity. Such behaviour does not provide immediate relief but can help absorb delayed effects. This is especially relevant, since we have shown that shocks can show delayed (negative) effects up to a year after the shock.

Another and rather drastic adaptive behaviour in response to famines has been migration. Most migration remains limited to migration from affected rural areas to cities within the same region [5] which in the DARTS framework is a logical response considering better market access of the urban areas. Some migration also occurs between regions, such as witnessed during the Irish famine in which Irish families migrated to the United States of America [42]. All these forms of adaptive behaviour, and more forms of adaptive behaviour, can in principle be added to the DARTS model. Simulating food security with and without such adaptive behaviour allows for simulating their positive and negative effects for people in different regions and for the world as a whole.

3.4 Broader implications

Policy interventions improving food security will be more effective when having a more solid scientific foundation. In complex systems, policy interventions such as an export ban can have (as we have shown) unexpected and undesirable consequences. It can be relevant to signal them in advance with a model rather than learning about them the hard way in reality. Modelling can help us think about systems and it is not the model predictions per se, but rather the insights that we gain from conceptualising and coding models and from defining scenarios and interpreting scenario outcomes that help us increase our understanding of shock effects on food security. Sometimes these insights are more easily gained from more abstract models (such as DARTS, or Sugarscape model by Epstein and Axtell [40]), even if in such cases accurate prediction or validation for any concrete case is less well possible with such abstract models.

The DARTS methodology challenges current approaches in food security research at annual and national scale, showing that intra-annual production, trade and food stock dynamics can cause hunger in one or few months of the year for particular fractions of the population. Such effects are averaged out and occluded from our sight when modelling at the national annual scale. An important insight is therefore the need to move beyond this national annual scale. In a similar vein DARTS challenges other neglected topics in current food security research, including (1) the interconnectedness of local and global scales (2) the rural/urban divide and (3) the important role of food stock dynamics. An important implication of the current work for the scientific community researching food security is that it provides a new approach for modelling food security that moves beyond many of the existing paradigms in food security research.

This being said we must also acknowledge DARTS is not a realistic land-use model or trade model. There are still large challenges with parameter estimation as we have discussed above. And challenges of adding more realistic behaviour to the model, including bottom up responses to shocks by individual agents (such as migration) as well as policy responses such as food relief aid. DARTS is still a prototype model with emphasis on more abstract modelling of the complex food trade system. At the time of writing, DARTS is still too abstract and too poorly parameterised and therefore in a too premature stage of model development to be considered for designing or evaluating concrete policy interventions.

4. Materials and methods

4.2 DARTS model

4.2.1 Schematic overview. DARTS [13] is an agent-based model (ABM) in which linked agents interact with each other and each individual agent has its own particular properties and behaviour (here limited to food trading plus for the farmers in particular months food production). Fig 7 presents a schematic overview of the DARTS model. A DARTS world consists of multiple regions (quadrants). Each region consists of an outer rural ring (green) and an inner urban ring (red). Urban agents are connected to both international and regional markets, while rural agents are only connected to regional (domestic) markets. DARTS has two types of traders: (1) international traders (core of Fig 7) linked to all urban consumers and linked to the industrial farmers and (2) regional traders linked to all farmers, rural consumers and urban consumers within their own region. Other agent types include consumers and farmers, which are subdivided into regional and industrial farmers (the latter having higher productivity). A DARTS world such as schematically shown in Fig 7 is set up through input files, with which can be configured for any given number of regions and agents.

Our model design philosophy acknowledges that a model is inherently a simplified representation of reality. The modeler determines the system's boundaries and decides which processes to include or exclude based on the specific objectives of the research. Our goal in the current paper was to develop new modelling capabilities to investigate the impacts of various potential shocks on global food security. All assumptions made should be interpreted within this context. These assumptions are grounded in the literature referenced in the introduction. Countries self-sufficiency and countries wealth differs and literature shows this has strong implications for food security, hence the in-silico world analysed contains richer and poorer regions and net importing / net exporting regions (Fig 8). Recognising the critical roles of food and wealth in food security, we modelled these elements (food and wealth) separately. For simplicity, we did not differentiate among various categories of food or cash. The rural/urban divide is also a significant factor, as historical data on famines illustrate that such crises can affect entire regions or be localised to just urban or rural settings. The food trade system is

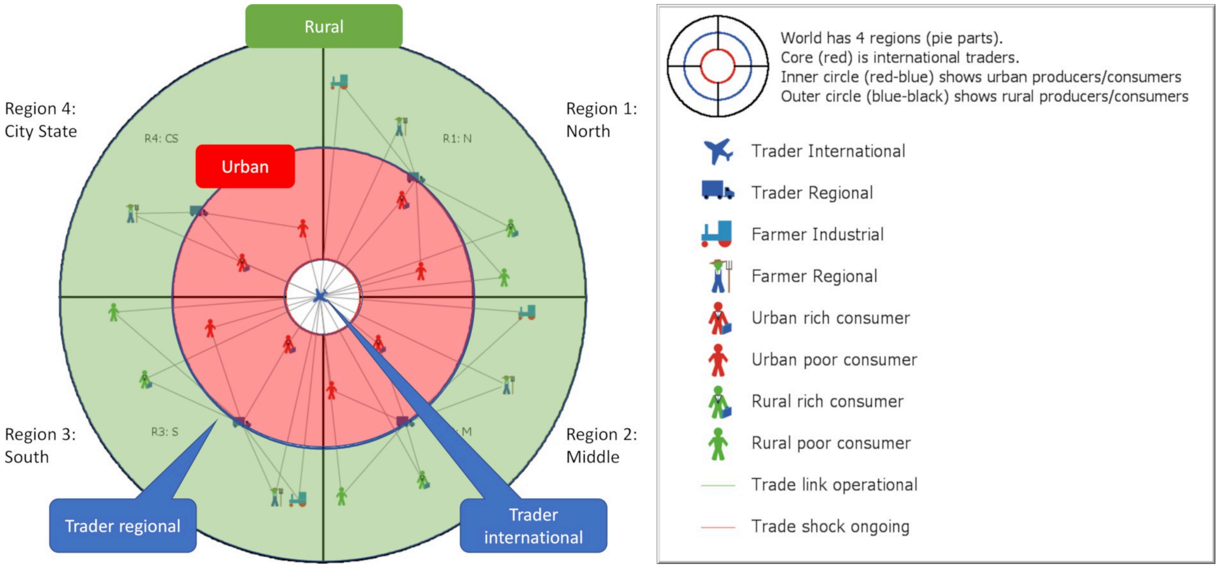

Fig 7. DARTS schematic overview. Left and right panel drawn with free Netlogo software [43], https://ccl.northwestern.edu/netlogo/docs/copyright.html

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markedly more intricate than our model suggests. It involves multiple food commodities and factors influencing healthy diets—not only calories but also vitamins and dietary diversity—all shaped by complex supply and demand dynamics. Trade value chains are in reality far more complex than the simple Producer-Trader-Consumer chain presented here. The assumptions employed in the DARTS model invite further scrutiny and provide fertile ground for future research. In the discussion section, we explore several promising avenues for extending this research, highlighting areas where our model can be refined and expanded to better mirror the complexities of real-world food security dynamics.

Different approaches are possible for modelling effects of shocks. General Equilibrium Model" (GEM) models are less suitable because they describe systems in equilibrium while the food system is clearly out of equilibrium after a shock. It is possible to also model food flows in a network using 'System dynamics' models (i.e. with differential equations). Yet as we write in section '3.3 Behaviour' we foresee future extensions of DARTS adding more individual agent behaviour. And for such extensions the ABM approach seems more appropriate.

4.2.2 Production and trade. DARTS runs at a monthly timestep. Each timestep entails the following actions:

1. All agents receive off-farm income;
2. Farmers produce food, depending on the month;
3. Shocks are applied (at random or user defined moment);
4. Farmers sell food to linked traders;
5. Consumers buy food from linked traders;
6. Consumers spend money on non-food;
7. All agents loose part of their stock;
8. Reporting.

Population

	All Regions	City State	Middle	North	South
Urban Rich	7345	100	2424	2433	2388
Urban Poor	1326	18	427	418	463
Rural Rich	1780		606	622	552
Rural Poor	321		107	107	107
Farmer regional	1070	2	337	281	450
Farmers 'industrial	158		59	99	
All Agents Total	12000	120	3960	3960	3960
% of world		1%	33%	33%	33%
% urban	72%	98%	72%	72%	72%
	All Regions	City State	Middle	North	South

Monthly food spending / Avg income

	All Regions	City State	Middle	North	South
Urban Rich	12%	8%	12%	10%	16%
Urban Poor	51%	35%	50%	42%	67%
Rural Rich	12%	8%	12%	10%	16%
Rural Poor	51%	35%	50%	42%	67%
Farmer regional	47%	31%	44%	37%	59%
Farmers 'industrial	8%		9%	7%	
All Agents Avg.	14%	10%	14%	12%	20%
	All Regions	City State	Middle	North	South

Annual self-sufficiency

	All Regions	City State	Middle	North	South
food requirement (TJ / year)	38	0	13	13	13
production regional (TJ / year)	15	0	5	5	5
production industrial (TJ / year)	27	0	9	18	0
production total (TJ / year)	42	0	14	23	5
food production / food requirement	1.11	0.08	1.12	1.83	0.41
	All Regions	City State	Middle	North	South

Fig 8. Key characteristics of the in silico world.

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We assume that farmers sell all of their food production to traders as is common in the developed world. Therefore, all consumers and farmers satisfy their food requirements by buying food from traders. The order in which sales are conducted is as follows:

Farmers' selling order. Industrial farmers first attempt to sell to international traders. Only if international traders have insufficient cash or if an Export shock is ongoing, industrial farmers will try to sell to regional traders. If a farmer cannot sell, due to shock or cash shortage of linked traders, then the farmer will stock the food him/herself and try sell again next month, in the same order of preference. Regional farmers are only linked to the domestic market and visit regional traders in random order.

Consumers buying order: wealthy to poor, preferably international. In a market economy price dynamics act as a sorting mechanism: in case of scarcity prices increase to the point where the poorest faction of the population may no longer be able to afford these elevated prices. A simpler sorting mechanism commonly used in agent-based models [28], and also in DARTS, is to order agents from wealthy to poor, which avoids the complexities of having to simulate price formation while still simulating stronger purchasing power for the wealthier agents. Each consumer agent visits all linked traders. Consumer's food purchasing stops when monthly food requirement has been met, if all linked traders' stocks have run out or if consumers' cash has run out. Urban consumers have a preference for buying from international traders. Urban consumers will only buy domestically if international stocks are finished, or if international stocks are inaccessible due to an Import shock. Rural consumers (including farmers) are only linked to the domestic market, they only visit linked regional traders.

4.2.3 Food security indicator. Each month for each individual agent we calculate consumption satisfaction as the ratio between food consumption and food requirement. A consumption satisfaction less than 1.0 indicates the agent consumed less than required. We calculated averages over a 3 and 12 month period, starting from the moment a shock was applied. 3/12 Month averages were calculated averaged over the world as a whole and averaged over each group of agents and each region.

4.2.4 Coding and visualisation. The DARTS model [13] is programmed in Netlogo version 6.4.0 [43]. Input files and output files are for current and earlier paper generated with 'r' software. For visualisations in the current paper, colours from the "Okabe-Ito" colour palette were used, a colour-blind-friendly palette [44].

4.3 In silico world

The emphasis of the current paper is on developing a deeper understanding the complex food system and the how, where and when of sensitivity to shocks. Prediction for any particular country or food commodity is impossible at the time of writing because worldwide data on the rural/urban divide, data on food reserves and data on trade networks are not available. We therefore introduce an "in silico" world based on general patterns that emerge from literature on regional and local case studies, which allows us to simulate effects of shocks on global, regional, urban and rural food security.

Fig 8 shows key characteristics of the in silico world. 1% Of world population lives in the City State, 3 large regions each contain 33% of world population. Each region (except the City State) has 72% urbanisation–this number is close to urbanisation projections for 2050, where [45] projects 68% of world population will be living in cities. Regional farmers receive 50% of their income as off-farm income, industrial farmers' income is purely from food sales and for the non-farmers all income is off-farm income. A recent study by Frelat et al. [46] shows the importance of off-farm income for food availability for farmers in Sub-Sahara Africa while in many European countries, off-farm income such as subsidies form a major source of total farm income. At given production levels, food requirement, food prices and income, agents spend between 8 and 67% of their income on food. This range is in line with values reported in [47]. Stock losses occur in all parts of the value chain. A fixed fraction of the stock is lost monthly (5%, based on [48]). Absolute food losses accumulate if food is stocked over longer period in time. For example if at the end of month 1 100 MJ is left in stock then 5 MJ is lost and 95 MJ is for sale next month. If none of this 95 MJ is sold then at the end of month 2 5% of 95MJ is lost and cumulative loss will be approximately 10MJ (~10%) over 2 months.

World total production is 11% higher than demand. This surplus is lost partially in different places of the value chain which leads to some hunger even in the simulated world without shocks (supporting material). Productivity differs between regions (Fig 8), with the North being a big exporter (self-sufficiency 1.83), the Middle being slightly positively self-sufficient, the South being a big net importer (self-sufficiency 0.41), and the City State producing almost no food of its own. These differences in self-sufficiency in the in-silico world as defined here are at the extreme end of country self-sufficiencies presented by [8]. We opted for such extreme differences in self-sufficiency to allow for modelling consequences of shocks in highly contrasting conditions. Parameters for harvest patterns were loosely based on [37] and are visualised in supporting material S1 Fig. In the in-silico world region North has a peak harvest in August; region Middle has two harvest periods and region South has its' peak harvest in February (6 months difference with North) due to opposite seasons in the Northern and Southern hemisphere. For the City State we assume continuous harvesting, as City States like Singapore focus on high value perishable goods (eggs, vegetables, [49]) produced year round.

4.4 Shocks

Table 1 presents an ontology of 6 distinct shock types shown in Fig 1. A shock scenario is defined as a simulation for a specific world (§4.2) with a specific set of shock parameters (Table 2). Similar to [29], a shock is defined by four parameters:

1. the moment at which it is applied, e.g. 7.5 years after start of the simulation;
2. the set of agents to which it is applied, e.g. domestic traders, e.g. Consumers in a particular region, e.g. industrial farmers in a particular region;
3. the duration of the shock, in number of months
4. the severity of the shock

From an infinite number of possible shock scenarios, we simulated but a few. The in-silico world presented in previous work has analogies with the real world but is not meant as an

Table 2. Shock scenarios.

Shock scenario	Years to shock	Shock duration (months)	Shock severity	description
0. Baseline (no shock)	7.5			
1. Crop failure in region X[1]	7.5	6	0.236	Starting in year 7.5 (June) during 6 months (June-Nov), harvest is 23.6% lower than normal
2. Crop failure + export shock in region X[1]	7.5	6 & 6	0.236 & 0.86	Combination of shock types 1 and 5
3. Cash shock in region X[1]	7.5	1	3	In one month, all ConsumerProducers[2] in region X lose 300% of their cash, which implies they are recovering from being debt for one or more months after the shock was applied
4. Hoarding shock in whole world	7.5	6	3	During 6 months, all ConsumerProducers worldwide seek to buy 3x the amount of food they normal buy
5. Export shock: farmers in region X[1] cannot export	7.5	6	0.86	During 6 months, export from the region is reduced by 86%
6. Import shock: consumers in region X[1] cannot buy from *international* traders	7.5	6	1	During 6 months, ConsumerProducers in the region cannot buy at all from *international* traders
7. Domestic trade shock: consumers in region X[1] cannot buy from *regional* traders	7.5	9	1	During 9 months, ConsumerProducers in the region cannot buy at all from *regional* traders

[1] We simulated the same set of 8 shock scenarios applied to two regions, region North and region Middle.

[2] in DARTS the agent type ConsumerProducer includes both farmers and non-farmers. A non-farmer is simply a consumer who produces nothing

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exact replication. Likewise also the scenarios analysed here are possible scenarios but no exact replications of any particular shock. Both serve to illustrate the DARTS methodology while our aim is not exact prediction.

Arbitrarily, we opted for a set of shock parameters that would double global annual average hunger compared with the baseline food security. In the baseline (No shock) global annual mean consumption satisfaction was 0.942, thus 0.058 below 1. We tuned shock parameters for region North such that they would lead to a doubling of dissatisfaction, i.e. global annual mean consumption satisfaction for any of these shock types is 1–2*0.058 = 0.884. Next the same set of shock parameters tuned for region North was applied to region Middle, to investigate how the same shock would have a different effect when applied in a different region. We thus simulated:

- the baseline (no shock scenario);
- 2 * 5 individual shocks applied in the two regions North and Middle;
- To demonstrate it is also possible to simulate effects of combined shock we simulated a common combination of shock types: the combination of a crop failure and export ban (e.g. [17,50])

The hoarding shock was applied to the whole world because it is so self-reinforcing: once one region starts hoarding other regions are triggered to do the same, or else be left empty handed.

Supporting information

S1 Fig. Shows Regional harvest patterns.
(PDF)

S2 Fig. Shows Three month (June-July-Aug) average consumption satisfaction since application of 8 shocks in region North.
(PDF)

S3 Fig. Shows Annual average consumption satisfaction since application of 8 shocks in region North.
(PDF)

S4 Fig. Shows Three month (June-July-Aug) average consumption satisfaction since application of 8 shocks in region Middle.
(PDF)

S5 Fig. Shows Annual average consumption satisfaction since application of 8 shocks in region Middle.
(PDF)

S1 Table. Shows the ConsumerProducer parameters, Potential data sources and their Limitation(s).
(PDF)

S2 Table. Shows the Trader parameters, Potential data sources and their Limitation(s).
(PDF)

S3 Table. Shows the Shock parameters, Potential data sources and their Limitation(s).
(PDF)

S4 Table. Shows Key variables for model validation, Potential data sources and their Limitation(s).
(PDF)

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