GLOBAL RELATIONS FORUM YOUNG ACADEMICS PROGRAM
ANALYSIS PAPER SERIES No.8

Famine Dynamics: The Self-undermining Structures of the Global Food System

DR. ASAF TZACHOR

Center for the Study of Existential Risk (CSER) and Center for Global Food Security, University of Cambridge

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This paper, entitled *"Famine Dynamics: The Self-undermining Structures of the Global Food System"* is authored by Dr. Asaf Tzachor as part of the *GRF Young Academics Program Analysis Paper Series.*

GRF convened the following group of distinguished members to evaluate and guide Asaf Tzachor's paper:

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Dr. Asaf Tzachor leads the "global food security and catastrophic risks" project, and the "artificial intelligence for agricultural supply chains risk management" project, both at the Center for the Study of Existential Risk, in the University of Cambridge. He is academic staff at the Cambridge Global Food Security Research Center. His research aims to better understand what shocks might threaten global food security, what the consequences of such disruptions may be, and how we can work to mitigate these risks; with a particular focus on emerging technologies. Asaf completed his postdoctoral research in the University of Cambridge, his doctoral work in UCL Faculty of Engineering Sciences, STEaPP, and studied Environmental Sciences in the University of Oxford. He was a Research Scholar at Columbia University, and a Lord Weidenfeld Scholar in Balliol College, Oxford.

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Famine Dynamics: The Self-undermining Structures of the Global Food System

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Abstract

Civilization has steered itself onto a vicious spiral. The modern system of agriculture, upon which global food security hinges, devours the planet's scarce supplies of fertile lands, fresh water, productive fisheries and forest ecosystems. 821 million lives hang in the balance, already suffering famine and all forms of malnutrition, while early signs of an even larger catastrophe begin to transpire. Instead of perpetuating self-undermining dynamics, the international science and policy communities should radically reform the methods of food production and provision. Systems thinking should lend insight.

1. Introduction

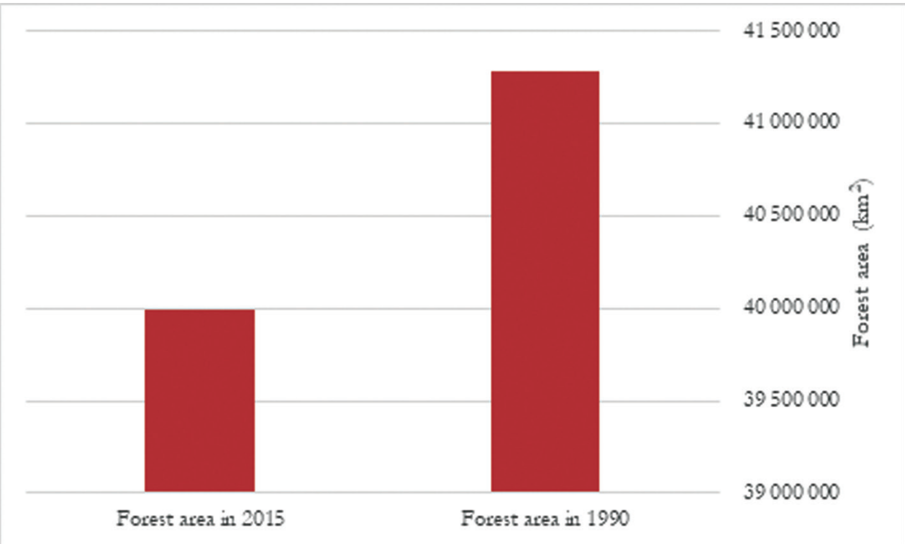
As it so often occurs, contemporary society has painted itself into a corner. In the perpetual pursuit of food security, a state in which nutritionally adequate, safe and affordable food is available to all people, at all times,[1] society has instituted a vastly sophisticated system of agriculture, globally-intertwined and ever-expanding, and one disproportionately organized around high-yielding, high-calorie crop varieties that require little attention and are easy to harvest and handle.

With the growth of an agricultural superstructure dedicated to merely a handful of staple crops, and not least, with the internationalization of trade, society's dependence on a limited number of crops, cropping systems, crop-exporting countries and commodity trading routes, grew decisive and perilous.

But the expansion of agriculture also resulted in deforestation of extraordinary proportions (see chart 1), loss of biodiversity,[2, 3] the exhaustion of fisheries, in emissions of greenhouse gasses and global warming, and these, in turn, are predicted to route back to undermine the very system that provoked them. In the words of Wright, society has maneuvered itself into a trap of progress.[4] Farming and fishing need to expand and intensify further to meet the food security requirements of over 7 billion people; projected to reach 8.5 billion within the next decade.

But the intensification of farming and fishing is poised to accelerate climate change, over-exploit the planet's scarce resources and saw off the branch civilization sit on.

Chart 1. Global forest area comparison (km2), 1990 and 2015.[5]



Systems Science, however, prevents us from believing in progress traps, paradoxes, and unintentional coincidences. As an alternative, Systems Science suggests to consider the tribulations associated with the modern system of agriculture as consequences of circular and dynamic structures: convoluted processes of cause-and-effect which tie together different elements of the system in interdependent relationships, and may breed environmental and humanitarian crises. These detrimental cascading dynamics warrant a systemic analysis of the global food system, food security and sustainability.

Furthermore, Systems Science allows us to circumvent disciplinary compartmentalization often found in scholarship, and bring together phenomena typically studied under separate disciplines: global warming, soil erosion, ocean acidification, malnutrition, and forced migration can be interlinked. Ecological and social risks, emanating by the food system; the pathways in which they mature, diffuse across states and sectors, and compound, can be better appreciated, and potentially prevented.

This paper for the Global Relations Forum builds on an ongoing research project on global food security and catastrophic risks conducted at the Center for the Study of Existential Risk (CSER) in the University of Cambridge, in collaboration with the Cambridge Global Food Security Interdisciplinary Research Center. It expands on similar recent activities,[6] while employing a more systematic, profound, and empirical approach to the topic, yielding better analysis for better policy interventions. Particularly, this paper explores four cause-and-effect processes, referred here as Circular Causality Structures.

These four structures include Agriculture and Climate Change *(diagram 2)*; the Collapse of Fisheries and Fisheries-dependent Livelihoods *(diagram 3)*; Global Warming, Crop Failures and Civic Unrest *(diagram 4);* Global Warming, Diseases Prevalence and Extreme Weather Events *(diagram 5)*.

The boundaries of the four structures are artificially outlined. No phenomenon discussed in this paper, biophysical or social, occurs in isolation and, in reality, all dynamics described here maintain some overlay with each other.

A short discussion of Circular Causality Structures precedes the analysis, and an examination of governance options and interventions in these four dynamic structures, concludes the paper.

This paper is not a work of foresight. The probabilities of scenarios are not calculated. Rather, this is an account of plausible unfolding of events and the structures provoking them. Centering on these four dynamics does not imply that other cause-and-effect structures do not exist. Different types of potential domino effects and obscure feedbacks are identified elsewhere,[7] some with potential pertinence to the global food system.

Two methods were employed to identify these four structures and tie effects to causes. Ten interviews were held with subject matter experts, long engaged with topics related to food security and agriculture. In the course of each interview, experts were asked to propose one or two detrimental domino effects (framed as "unintended consequences") emanating from the expansion and intensification of modern agriculture. The one condition: chains must route back (i.e. operate in circular pathways) to disrupt yields or agricultural supply chains. The author then concentrated on the prevalent structures suggested. An extensive literature review of over 130 sources complemented interviews.

2. Circular Causality Structures

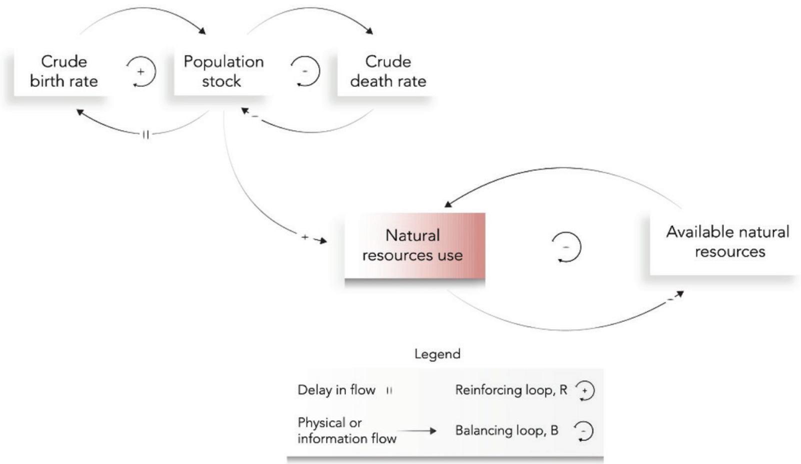
Circular causality structures[8] or feedback structures are the processes through which various phenomena, such as climate change and ocean acidification, or specific circumstances, such as food security, are brought into being.[9,10,11]

There are two types of circular causality structures: reinforcing and balancing. Reinforcing structures, also termed positive feedback loops, occur if one system component produces more of a second system component which then feeds-back to produce more of the first component. Eventually, a chain of reinforcing reactions may gain sufficient momentum to throw a system out of balance, so referring to these structures "positive" may be misleading: vicious cycles like social inequality and poverty,[12] or the disastrous ice caps melting–albedo-climate change feedback are considered "positive loops" too.[13]

In contrast, balancing structures, referred to as negative feedback loops, occur when one system component produces more of a second system component which routes back to produce less of the first component. Balancing structures stabilize systems by resisting disruptions.

Notably, these dynamics structures consist of delays. A delay is the period of time by which a change in one component incites a change in another. For instance, the time required for greenhouse gas emissions to build up in the atmosphere and increase global temperatures (see diagram 1).

Diagram 1. Example of circular causality structure



3. Four Structures Undermining the Food System

When discussing the dynamics of famine and food insecurity, not all circular causality structures deserve equal treatment. Some structures, more than others, demonstrate the system's most perverse and self-undermining behaviors as well as exert disproportionate influence over the future.

This paper describes four cause-and-effect dynamics. These four dynamics include Agriculture and Climate Change (*diagram 2*); the Collapse of Fisheries and Fisheries-dependent Livelihoods (*diagram 3*); Global Warming, Crop Failures and Civic Unrest (*diagram 4*); Global Warming, Diseases and Extreme Weather Events (*diagram 5*).

Centering on these four dynamics does not imply that additional circular causality structures do not exist. Different types of potential feedbacks are identified in literature,[14] some with pertinence to the global food system.

Furthermore, in all dynamics underlying socio-economic inequalities serve as food security risk multipliers. While these relations are registered in literature,[15], [16,17] they are under-discussed in this paper directly, and are accounted for as an aspect of food security, which covers equal and affordable access.

To center on few fundamental structures, two complementary methods were employed. First, ten subject matter experts, long engaged with topics related to food security and agriculture, were interviewed. Experts were either currently or formerly officially associated with the Intergovernmental Panel on Climate Change of the UN (IPCC), the Food and Agriculture Organization of the UN (FAO), and the Consultative Group on International Agricultural Research (CGIAR).

During each interview, experts were asked to suggest one or two detrimental domino effects (framed as "unintended consequences") originating from the expansion and intensification of modern agriculture, with one condition: proposed chains of cause-and-effect must route back to disrupt yields or agricultural supply chains (i.e. operate in circular, self-undermining, pathways). The author then concentrated on the most prevalent structures suggested. Second, an extensive literature review of over 130 sources was used to both triangulate and complement information obtained in interviews.

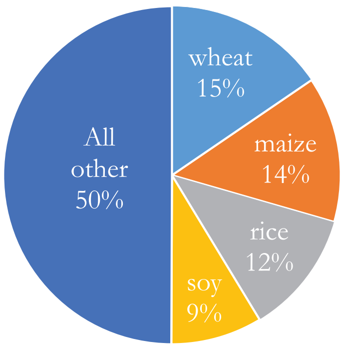
4. Agriculture and Climate Change Dynamics

Human hunger, and the fear of famine, are the beginning and the end of the circular structures. They have inspired agriculture since time immemorial. And when crop failed and agriculture floundered, they have resulted in riots and revolts.

As the global population continues to expand, the motivation to intensify agriculture further endures. Furthermore, as the share of the middle-class of that global population increases, changes in dietary preferences towards a Western-type diet and higher meat and dairy consumption,[18,19,20,21,22,23] are exacerbating the struggle over finite arable lands.[24] The livestock economy, which provides the middle-class with animal-source foods (ASF) depends on a constant supply of animal-feed – certain staple crops used for animal husbandry, mainly maize and soybean.[25,26] Crops that are cultivated on fertile lands which otherwise would have been farmed for plant-source foods (PSF).[27,28]

The consequence of these demographic and dietary drivers is an undiversified global agricultural system disproportionately organized around four high-yielding, high-calorie crop varieties that require little attention and are easy to harvest and handle: wheat, maize, rice and soybean, for both food and animal-feed. Together, these four items occupy roughly half of the global cropland under cultivation (see chart 2).

Chart 2. Top one hundred global staple crops by area (FAOSTAT, 2017)



This global structure, as stated above, is underpinned by a simple motivation: a constant need to expand and intensify production, bringing in more territories under farming while increasing crop yields per area.[29,30,31]

These, however, entail enhanced emissions of greenhouse gasses. Agricultural supply chains, of plants and livestock, from farm to fork, are responsible for a third of all anthropogenic greenhouse gas emissions, both carbon dioxide (CO2) and methane (CH4).[32,33,34]

Charts 3-7. The share of greenhouse gas (GHG) emissions of the agricultural sector of the total GHG emissions (million tonnes of CO2 equivalent), for selected countries.[35]

Chart 3. Brazil

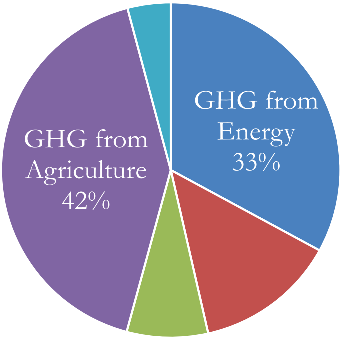


Chart 4. India

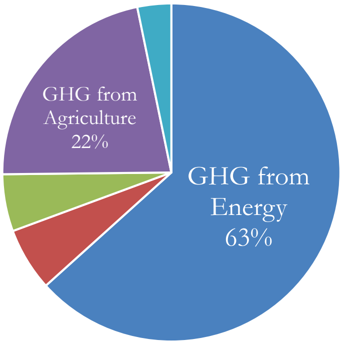


Chart 5. Kenya

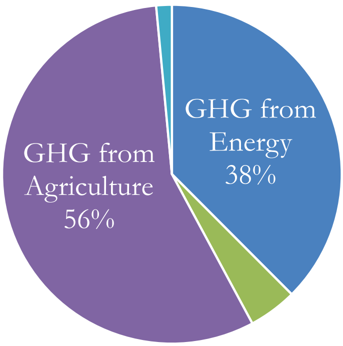


Chart 6. Nigeria

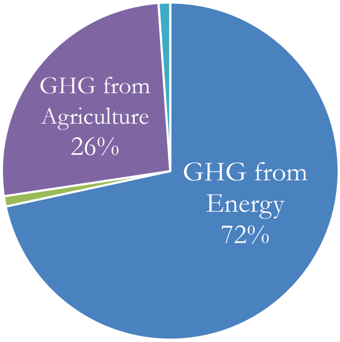
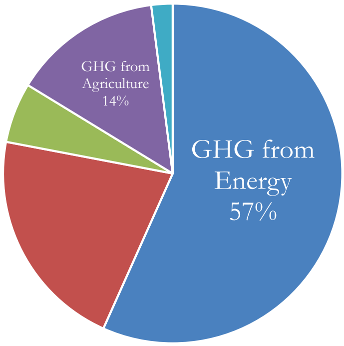


Chart 7. France



In the course of time, the concentration of carbon dioxide and methane in the atmosphere rises and, ultimately, average global temperature increases. Ice stored in the arctic sea or in tundras – treeless regions in the Arctic – melts,[36] and when it does, surface albedo – the energy reflected back by a surface – decreases. More solar energy is subsequently absorbed leading to an increase in ocean temperatures. Sea ice dissolves quicker as a result (think of floating ice cubes in a jug of warm water) until sudden and massive regime shifts occur and 11 billion tons of ice are lost in a single day.[37]

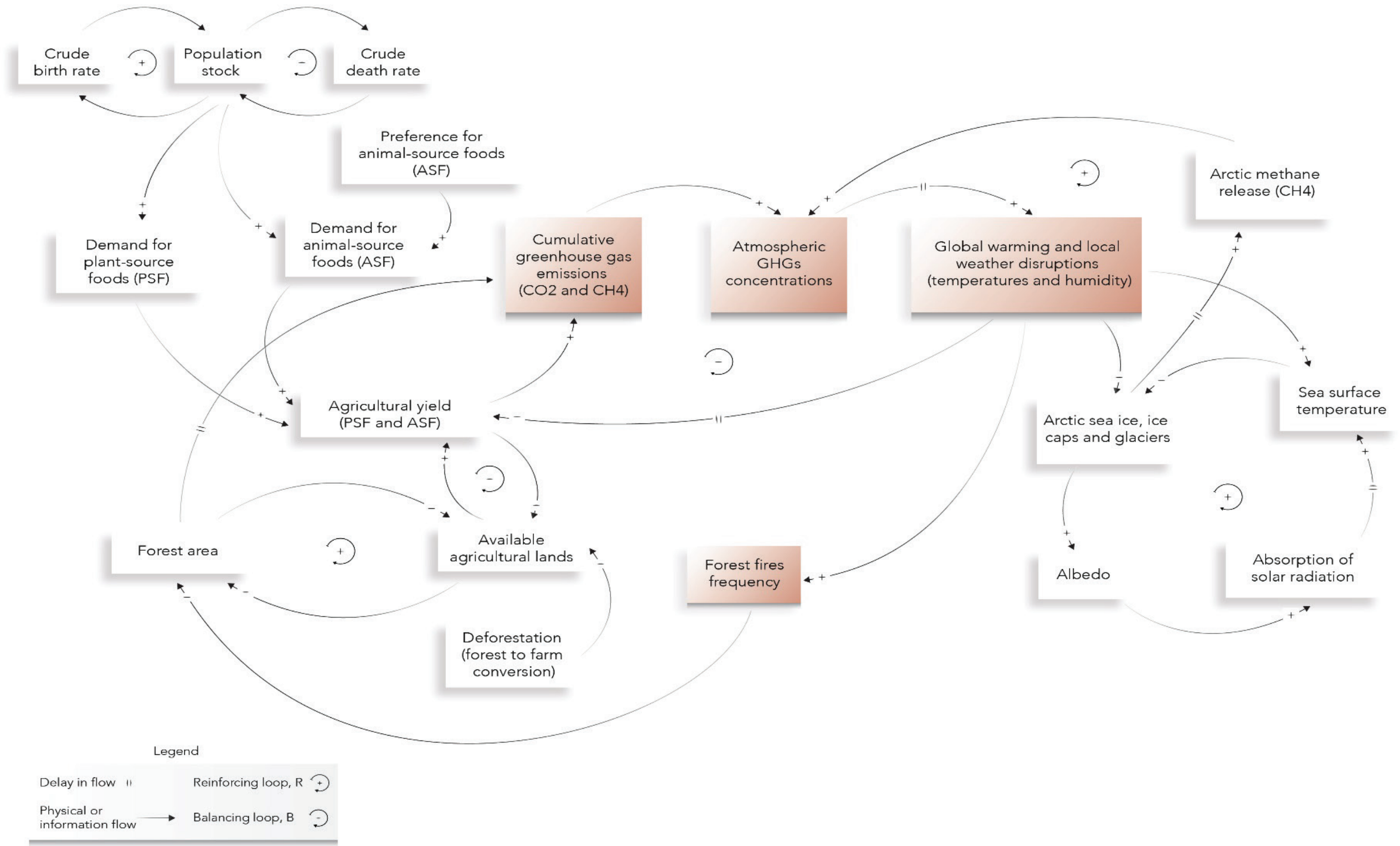
These regime shifts are also known as "tipping points", and in the context of climate change and ice sheets, a recent research warned of "the growing threat of abrupt and irreversible climate changes", in which, "the Amundsen Sea embayment of West Antarctica might pass a tipping point and [...] when this sector collapses, it could destabilize the rest of the West Antarctic ice sheet like toppling dominoes – leading to about 3 meters of sea-level rise on a timescale of centuries to millennia."[38]

Repercussions continue to cascade through the system (see diagram 2). Global warming intensifies the frequency of wildfires to the extent that Stephen Pyne declared that "humans have created a Pyrocene [...] a Fire Age equivalent in stature to the Ice Ages of the Pleistocene [...] heading into a no-narrative future

[…] immense and unimaginable."[39] In Brazil, in just 7 days in August 2019, 109,694 wildfire alerts were registered.[40] Around the same time, in Alaska, over 1.5 million acres of boreal forests burned down.[41] In these circular causality structures, boreal forests are vitally positioned. They function as global "carbon sinks" absorbing carbon dioxide from the atmosphere.[42,43] Incinerating boreal forests, wildfires in Alaska discharged a hundred megatons of CO2 back into the atmosphere.

Eventually, through warming, wildfires and altering weather patterns, climate change routes back to disrupt agriculture. The availability and affordability of food depend on agricultural yield and consistency in yield, which in turn depend on crop tolerance to environmental stress factors.[44] In other words, cropping systems are vulnerable to variations in heat, humidity and precipitation.[45] The destabilization of regional and seasonal weather patterns enhances these vulnerabilities. One study found that changing meteorological conditions have decreased the global production of wheat by 5.5% and of maize by 3.8%, between 1980 and 2008.[46]

Diagram 2. Circular Causality Structure: Agriculture and Climate Change



5. The Collapse of Fisheries and Fisheries-dependent Livelihoods Dynamics

For fisheries, the release of carbon dioxide into the atmosphere provokes several detrimental chain reactions. Carbon-induced ocean acidification[47,48,*] coupled with alternations in ocean salinity from melting ice caps and glaciers, and with ocean warming[49,50] alters the chemistry of the oceans and destabilize marine ecosystems.[51]

Studies in the Arctic, for instance, indicated a decrease in the mean abundance of fish species due to ocean warming.[52] Similar observations were noted elsewhere, with potential implications for catch.[53] In the Mediterranean basin, climate change is postulated to cause morphological changes, specifically a reduction in fish sizes.[54]

A recent research by Lenton et al. (2019:593) noted that heatwaves led to "mass coral bleaching and to the loss of half of the shallow-water corals on Australia's Great Barrier Reef. A staggering 99% of tropical corals are projected to be lost if global average temperature rises by 2°C [...] this would represent a profound loss of marine biodiversity and human livelihoods".

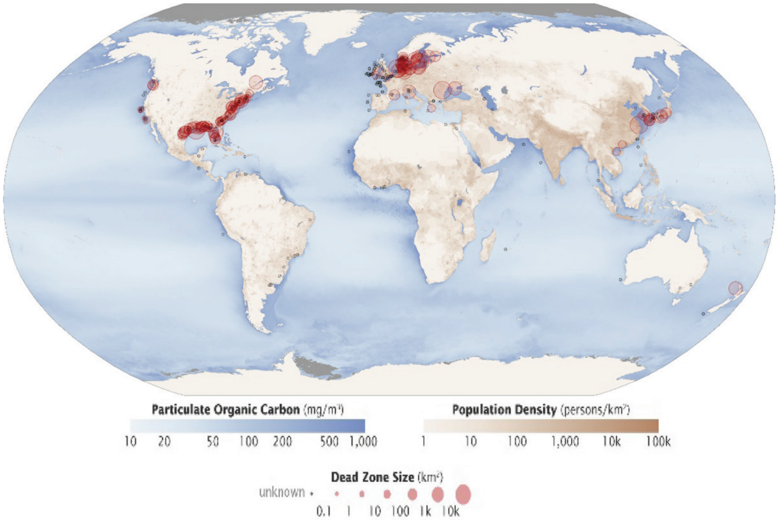
Declining ocean productivity is affected by additional natural and anthropogenic factors, such as ultraviolet radiation from ozone depletion, and toxic pollutants, including volumes of plastic,[55] but is critically compounded with the over-exploitation of fisheries, and illegal, unreported, and unregulated (IUU) catch.

Of the 600 largest global fish stocks monitored by the FAO, fifty-eight percent are fully exploited, thirty-one percent are overexploited at unsustainable levels, and a few specific stocks have collapsed and can no longer serve as a food resource. North Atlantic cod and haddock are depleted. Bluefin tuna is on the brink of exhaustion. Salmon is fully exploited. In the eastern-central Atlantic, virtually all fish species are overexploited. In the Indian Ocean, fish species are either exhausted or over-exploited. In the Pacific Ocean, most fish species are either depleted or over-exploited, and the South China Sea fishery is on the edge of collapse.[56]

Critically, animal-source foods rely upon crop production, for feed, which uses vast quantities of fertilizers, mainly nitrogen and phosphorous. Over fifty percent of those fertilizers drains away into rivers, and eventually, estuaries, where they create aquatic dead zones of low-oxygen waters and disrupt fisheries further[57](see map 1).

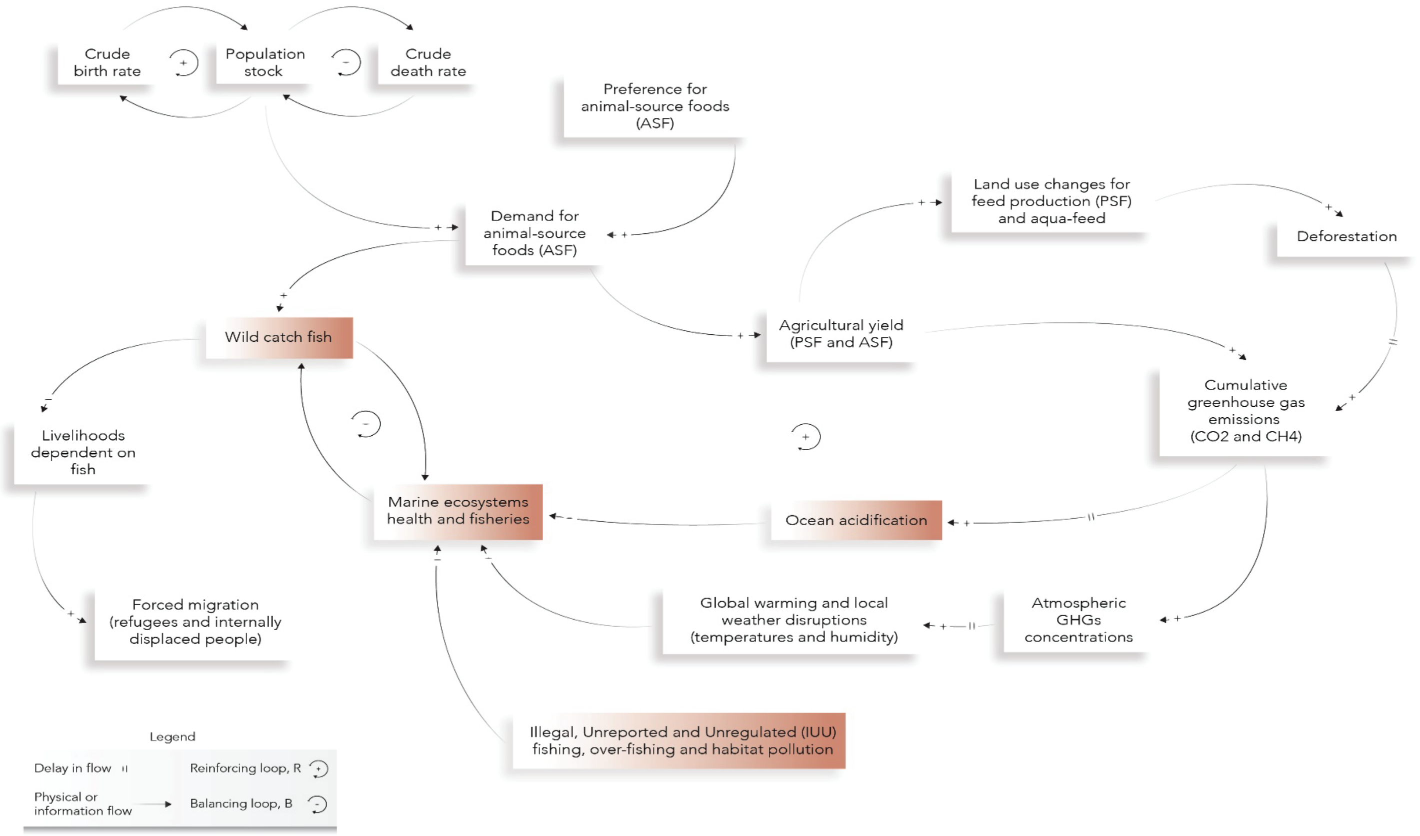
* According to UNESCO (2020), the acidity of oceans has increased by 30 percent since the beginning of the Industrial Revolution. This increase is 100 times faster than any change in acidity experienced by marine organisms for the last 20 million years.

Map 1. Aquatic dead zones.[58]



Hundreds of millions of lives and livings, utterly dependent on fisheries, are affected.[59,60] Globally, fish and seafood provide some seventeen percent of animal-proteins intake, and in several developing countries, this figure is as high as fifty percent.[61] The fishing sector also accounts for some 50 million households with jobs and income.[62] When fisheries are finally exhausted, fishermen will be forced to migrate (see diagram 3).

Diagram 3. Circular Causality Structure: Collapse of Fisheries and Fisheries-dependent Livelihoods



6. Global Warming, Crop Failures and Civic Unrest Dynamics

Crop yields and consistency of yield are vulnerable to changes in precipitation regimes,[63] and consequently, to climate change.[64] Shifting patterns of precipitation affect soil water availability during the growing season and were held accountable for crop failures before.[65] Droughts are especially hazardous for smallholder farmers in developing countries. One study noted that "in semi-arid and sub-humid agroecosystems […] frequencies of both meteorological droughts and dry spells are predicted to increase with climate change […] while dry spells can be bridged through investments in appropriate water management techniques, crop yields cannot be sustained during a meteorological drought."[66]

With weather disruptions and water scarcities becoming increasingly prevalent, crop yields will slow down in many vulnerable regions. When crops will fail, prices will rise, and societies will resort to riot, revolts and famine.[67,68,69,70]

The International Food Policy Research Institute (IFPRI) indicated that the 2007-2008 food crisis sparked civic unrest in 61 countries and led to violent riots in 23 countries.[71] Food insecurity was also believed to be a contributing factor to the protests and violent revolts in Tunisia, Egypt and Libya, referred to as the Arab Spring.[72] In like fashion, the civil war in Syria was attributed to changes in regional climate and precipitation patterns.[73] In the Horn of Africa, in 2011, droughts led to food shortage, harming 13 million people, and in Somalia, it has claimed the lives of over 250,000 people.[74]

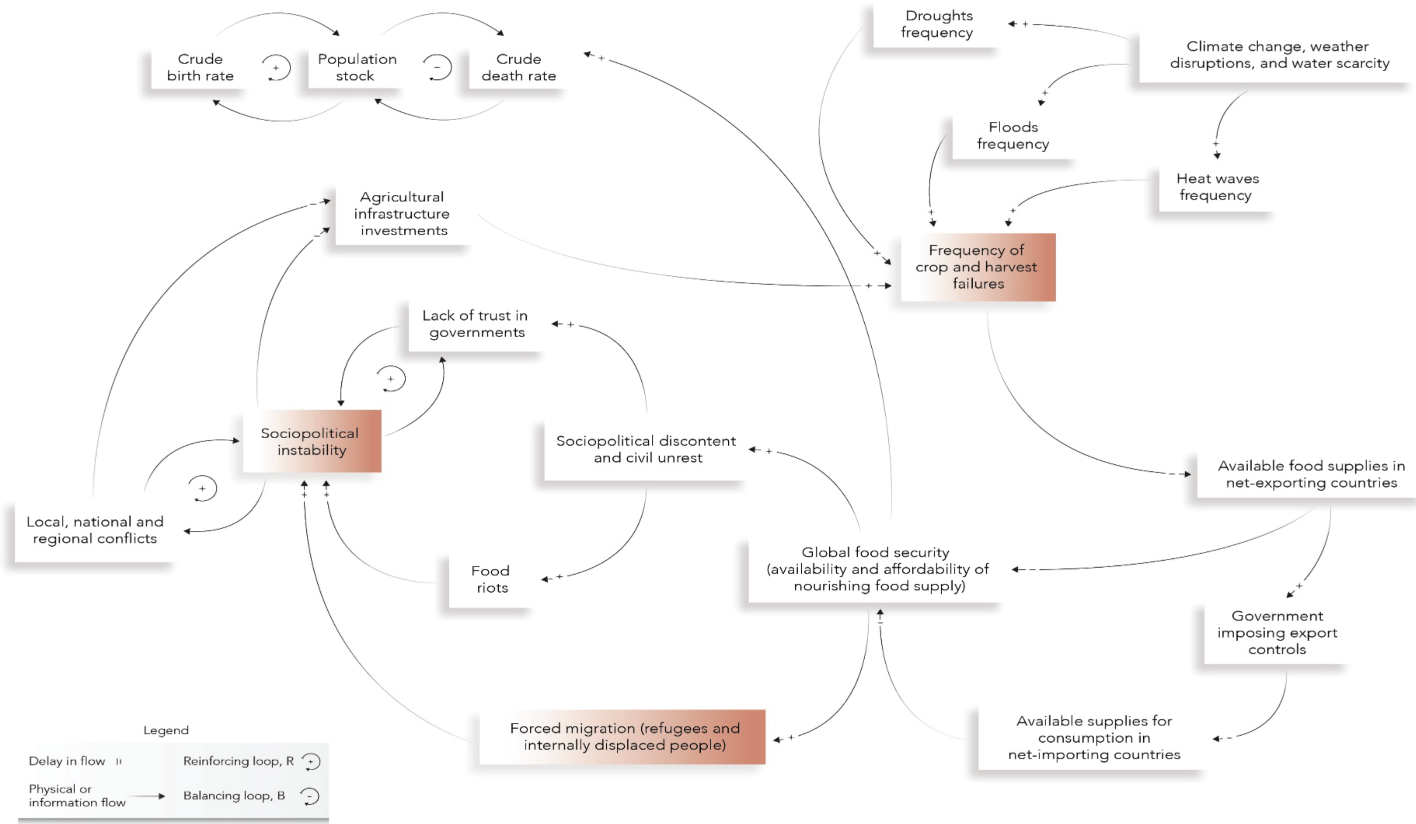
One chain reaction of these dynamics, starvation-struck individuals would migrate, as refugees or internally displaced persons (IDP). As a former Executive Director of the World Food Programme noted "hunger is on the rise… one billion people are going hungry every day… without food, they have only three options: they riot, they emigrate, or they die". The IPCC gave notice that "changes in climate can amplify environmentally induced migration both within countries and across borders […] extreme weather and climate or slow-onset events may lead to increased displacement, disrupted food chains, threatened livelihoods […] and contribute to exacerbated stresses for conflict."[75]

The flow of immigrants will disturb public order, incite racial intolerance, and inspire socio-political discontent and strife.

Admittedly, crop failures and resulting food riots will vary from region to region.[76,77] Collectively, however, the exodus of forced migrants and climate refugees will endure.[78,79]

In such circumstances, essential foreign direct investments in climate adaptation in agriculture would be discouraged,[80] preserving vulnerabilities, increasing the frequency of crop failures, and reinforcing the feedback loop (see diagram 4).

Diagram 4. Circular Causality Structure: Global Warming, Crop Failures and Civic Unrest



7. Global Warming, Diseases Prevalence and Extreme Weather Events Dynamics

Climate change is poised to aggravate three more risks that, if materialized, will disrupt or disable agricultural supply chains: plant diseases, livestock diseases, and extreme weather events.

Considering plant diseases, climate warming is estimated to enhance the survival rates of bacteria and viruses, as well as of ectoparasites.[81] The risk of epidemics will similarly increase.[82] According to the IPCC, "there is robust evidence that agricultural pests and diseases have already responded to climate change resulting in both increases and decreases of infestations."[83]

The spread of locus swarms in East Africa in 2020, in Kenya, Ethiopia and Somalia, is estimated to be the most severe invasion of desert locusts in decades,[84] and climate change has been hypothesized to play a crucial role in it.[85]

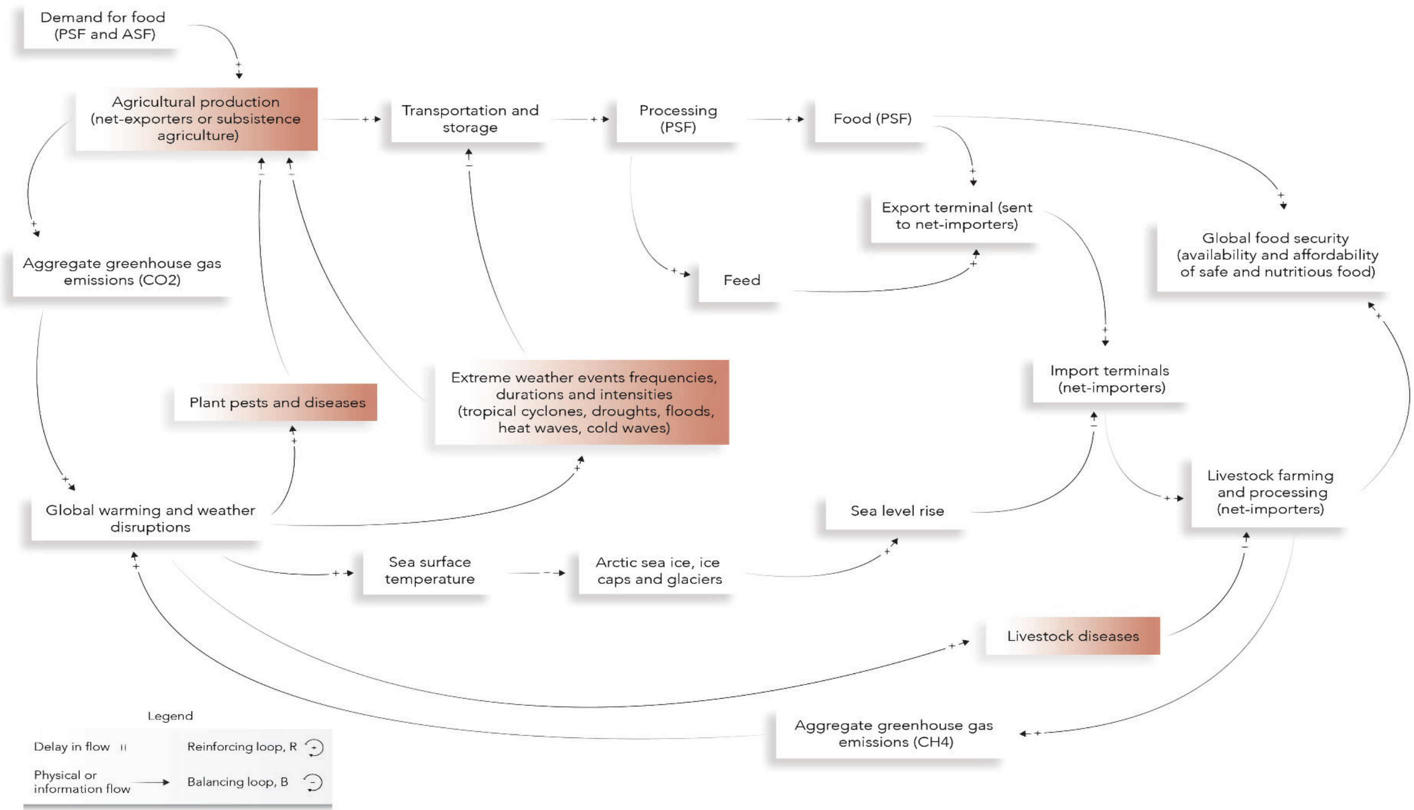
Concerning livestock diseases, warmer weather is expected to contribute to the spread of infectious diseases, such as bluetongue, camelpox and chicken anemia, and their frequency of outbreaks,[86,87] with greater ferocity, and graver consequences in developing countries.[88]

At the same time, the frequency and intensity of tropical cyclones, monsoons, storm surges and floods will rise. At every phase and function of agricultural supply chain, freak climate-related incidents are projected to damage critical infrastructures,[89] cripple value chains, and exacerbate agricultural commodity price volatility.[90,91]

If these assessments were to realize, then the 1989 Kavali Cyclone in Thailand, Andhra Pradesh cyclone in Southern India a year later, the 1991 Bangladesh cyclone, Hurricane Katrina in the Gulf of Mexico in 2005, Cyclone Nargis in Myanmar in 2008, and Typhoon Haiyan in Philippines in 2013 – together leaving millions in malnutrition and farmlands in ruins – should be regarded a prelude to a very violent twenty-first century.

In the meantime, melting ice sheets and glaciers, and resulting higher sea levels, will wipe out coastal farmlands and upset logistics at importation and exportation terminals through which approximately eighty percent of global food trade is directed[92] (see diagram 5).

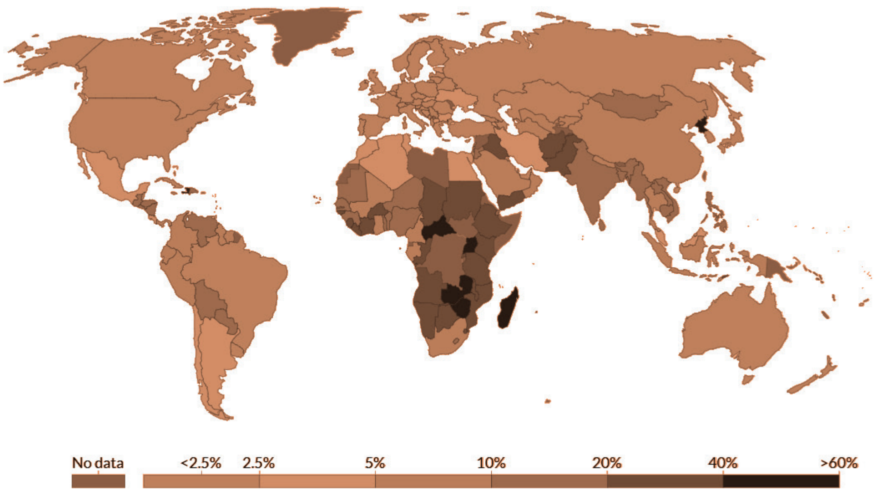
Diagram 5. Circular Causality Structure: Global Warming, Diseases Prevalence and Extreme Weather Events



8. Discussion: Governance and Leverage Points

The global food system is constrained by finite resources, it is constructed around a small quantity of ease-to-handle staple crops, it is prone to operational instabilities and vulnerable to a host of biophysical risks. The system fails on its fundamental promise: to prevent micronutrient deficiencies and famine. 821 million lives are currently affected, suffering all forms of malnutrition (see map 2 for FAO hunger indicator) and at the same time, the agricultural complex is a major contributor to soil erosion, deforestation, ecosystems collapse and global warming. The latter, stimulates ocean acidification, wildfires and extreme weather events.*

Map 2. FAO hunger indicator: share of the population that is undernourished, i.e. has a caloric intake insufficient to meet the minimum necessary requirements.[93]



While a myriad of mechanisms governs the food system's self-destabilizing behaviors, and an array of cascading effects ripple through associated ecological and social structures, this paper sought to recognize several cause-and-effect dynamics, that – according to experts, and literature – deserve immediate consideration, and action. These four structures included Agriculture and Climate Change *(diagram 2)*; the Collapse of Fisheries and Fisheries-dependent Livelihoods *(diagram 3)*; Global Warming, Crop Failures and Civic Unrest *(diagram 4)*; Global Warming, Diseases Prevalence and Extreme Weather Events *(diagram 5)*.

* Certainly, other factors lead to these detrimental conditions. For instance, the energy sector is a major contributor to climate change, and the mining sector is a major contributor to deforestation.

One thing observed and agreed, the global food system is not an ideal one. And yet, the prevailing interventions employed by the food policy community are incremental, counterproductive and warrant critique. Gradual adjustments of the system to a changing environment, such as cropland expansion and agricultural intensification – the two predominant strategies of the global agricultural complex,[94] will neither achieve sustainable food security nor avoid ecological degradation and habitats destruction.

Farmland expansion will be a precarious undertaking.[95,96] Already a third of the world's arable lands are moderately to exceedingly degraded (i.e. eroded), due to intensive agriculture and removal of vegetation cover.[97,98,99] It was also noted that there are scarce opportunities left for increasing agricultural areas.[100] Bleakley and Hayes indicated that "previously utilized methods of intensifying agriculture will soon no longer be an option due to the high impact trade-offs they have on the environment, including fragmenting natural habitats and threatening biodiversity, production of greenhouse gases from land clearing, fertilizers and animal livestock production, and nutrient run-off from fertilizer damaging marine, freshwater and terrestrial ecosystems."[101] Nelson et al. and Tilman et al. noted similar limits for farmland expansion.[102,103]

Intensification of yields should be equally problematic. Even though advancements in crop sciences improved agricultural yields, the rate of demand – driven by a swelling population with a penchant for animal-source foods – is projected to exceed both the rate of crop production,[104] as well as the rate of agricultural intensification.[105,106,107]

The necessity to substantially improve the system of agriculture features in literature often,[108,109] and yet, yields intensification – a "more of the same" approach – continues to serve the foremost strategy to ensure food security. [110,111,112,113,114,115,116,117,118,119,120,121]

To prevent catastrophic humanitarian crises, systemic interventions should be reevaluated, and the system of agriculture overhauled. Destructive circular causality structures, critical dependencies and distortions should all be abated, if not abolished. The international communities of scientists, agri-technologists and food policy makers should reexamine their approach, and Systems Science – this paper proposes – should guide these reconsiderations.

From the standpoint of Systems Science, effective and efficient interventions in complex nonlinear systems are those that make full use of "leverage points": critical places in the dynamics where a minor adjustment in one element engenders a substantial change in the entire structure.[122] Meadows (ibid) prescribed twelve such points, in increasing order of effectiveness, in terms of systemic transformation (see table 1).

Table 1. Places to intervene in a system, in increasing order of effectiveness (adapted from Meadows, 1999[123])

Places to intervene in a system
Change constants and parameters
Change sizes of buffers
Change structure of material stocks and flows
Change lengths of delays
Change negative feedbacks strength, self-correction capacity
Change gain around driving positive feedback loops
Change structure of information flows
Change rules of the system
Add, change, evolve, or self-organize system structure
Change goals of the system
Change mindset or paradigm out of which the system — its goals, structure, rules, de-lays, parameters — arises
Transcend paradigms (i.e. no one paradigm is true)

The boundaries of this work prevent a comprehensive analysis of potential interventions and their expected effectiveness, as well as a full discussion of implication for policy emanating from the circular causality structure identified in this work.

Nonetheless, two principles should be weighed when applying systems thinking for agri-technology and food policy.

First, while the circular causality structures illustrate some recurring themes (e.g. demand for animal-source foods drives deforestation, greenhouse gas emissions and the exhaustion of marine and terrestrial ecosystems), no one single intervention is capable of transitioning the system into a more sustainable state. The notion of "simple solutions" or "silver bullets" should be categorically rejected. Instead, a cocktail of interventions, a suite of strategies, should be concocted and delivered.

Table 2 below identifies initial intervention strategies, as examples. The table draws on propositions already recognized in scientific literature and policy papers. Yet, this is in no way an exhaustive catalog, nor is it peer-proposed, nor peer-reviewed. It should be stated then, that all twelve leverages ought to be explored in a methodical manner. The purpose of the table is to demonstrate that various interventions have already been underlined (see table 2).

Table 2. Initial interventions in the global food system, in increasing order of effectiveness (based on Meadows, 1999, and expanded)

Places to intervene in a system	Intervention examples
Change constants and parameters	Modify agricultural subsidies,[124] incentives,[125] and safety standards
Change sizes of buffers	Increase grain storage silo capacity[126,127]
Change structure of material stocks and flows	Improve transport networks and reduce dependence on chokepoints[128]
Change lengths of delays	Improve forecasting of supplies, demands and prices[129]
Change negative feedbacks strength, self-correction capacity	Reduce price volatility
Change gain around driving positive feedback loops	Sponsor positive self-reinforcing dynamics
Change structure of information flows	Make information available, accessible and secure[130,131]
Change rules of the system	Change penalties and constraints schemes, strengthen regulation and supervision of illegal, unre-ported, and unregulated (IUU) fishing
Add, change, evolve, or self-organize system structure	Encourage variability, experimentation and diversity in crops and cropping systems, as well as in future foods[132]
Change goals of the system	Promote agricultural self-sufficiency[133]
Change mindset or paradigm out of which the system — its goals, structure, rules, delays, parameters — arises	Identify anomalies, asymmetries and failures, and design differently[134,135,136,137]
Transcend paradigms (i.e. no one paradigm is true)	To be explored

It should be well registered that any intervention in a casual mechanism described in this paper may provoke fluctuations and disturbances in entities at the systems' external environments. To restate, the boundaries of the four mechanisms in this paper are arbitrarily outlined.

There is a second principle to consider before systems thinking is applied for agri-technology and food policy.

While the dynamics and processes suggested in this work unfold at the global level, their repercussions are asymmetrically experienced at the regional, national and local theaters and, thus, a more nuanced approach is mandatory when state-level interventions are debated and devised. Circular causality structures and leverage points, therefore, should be context-sensitive, and context-informed. Here too, system theory should lend insights.

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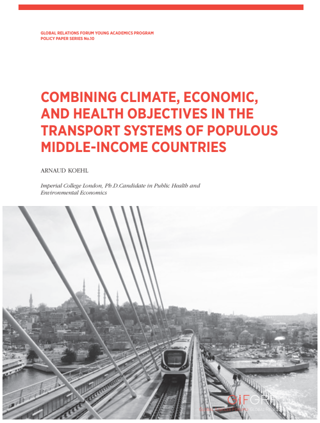

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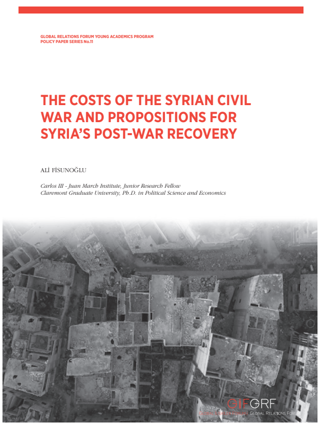

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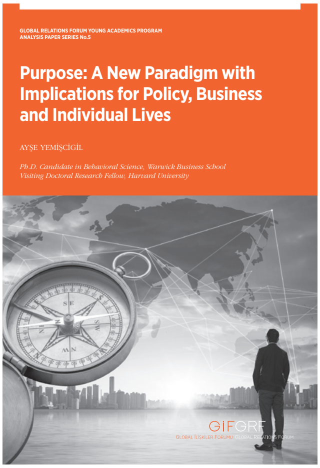

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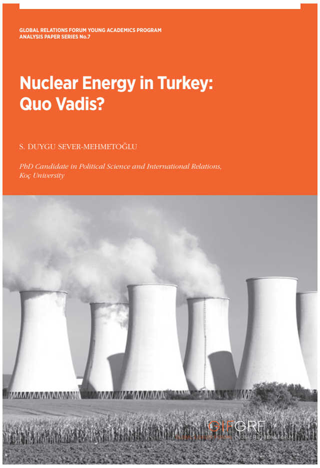

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