Lock-in mechanisms in global food systems: implications for sustainability and food security.

Thesis submitted by

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To my wife Gabi, to my mother Estela, to my father Ricardo, to my brother Gabriel,

and in loving memory of my grandmother Sara and my aunt Vera,

for their love and resilient support throughout my many mistakes and few triumphs in the pursuit of interdisciplinarity beyond convenient paradigms.

Declaration

I confirm that this is my own work and the use of all material from other sources have been properly and fully acknowledged.

André Zuanazzi Dornelles

Reading, September 2021

5. Systemic food risks: synchronised dynamics of shocks to national food availability and supply

Lock-in mechanisms in global food systems: intertwined social-ecological dynamics for sustainable development.

As global food networks increase in size, complexity and interconnectivity, a systemic understanding of the emergent drivers and coevolving trajectories that can either enable or hinder the transformation of food systems towards more sustainable trajectories is sorely needed. In this thesis, an interdisciplinary approach building from the literature of resilience, sustainability, and systemic risks was developed to investigate and quantify intertwined dynamics in food systems that can reinforce undesirable outcomes in social-ecological systems (i.e., lock-in mechanisms). In the four manuscripts collected, we aimed to, respectively: 1) investigate diverse interpretations of 'undesirable resilience' and explore potential commonalities from an interdisciplinary understanding, 2) operationalize a comprehensive understanding between the undesirable properties of resilience and their impacts on transformations towards sustainability throughout four case studies, 3) quantify multiple human and environmental dimensions of food systems transformations archetypes to identify potential leverage points for sustainability transformations, and 4) empirically investigate dynamic and shared patterns of interannual fluctuations of dietary energy supply and food supply and their implications for systemic food risks. Some key results include how the term 'lock-in' was found to be a bridging concept for an integrative understanding of social-ecological system dynamics (as found in manuscript 1) and can help to reveal mechanisms to enable systemic transformation towards sustainable development (elaborated in manuscript 2). The transformation of global food systems tended to be locked-in trajectories of expanding agricultural output, whilst accompanied by increasing malnutrition and environmental pressures (i.e., transformation archetypes) – which were found independently of improvements to productivity (quantified in manuscript 3). These social-environmental impacts are likely to co-occur across countries (i.e., interlocking mechanisms), with important implications for systemic risks. Dietary energy supply and food supply showed synchronised dynamics across nations, which were partially explained by geographic distance (assessed in manuscript 4). Collectively, lock-in mechanisms in global food systems reveal important conceptual, methodological, and empirical advancements to explore sustainable pathways for development and transformation.

I would like to thank all academics and students directly and indirectly involved in this project. The University of Reading provided a truly encouraging platform to conduct my research, to collaborate with researchers from multiple disciplines, and to grow professionally and personally. During my PhD journey, I was also able to engage with fascinating experiences outside of the scope of this thesis – for instance, acting as postgraduate researcher representative in diverse committees (e.g., within the School of Biological Sciences, the Graduate School, and the Committee on Researcher Development and Postgraduate Research Studies) and jointly designing research exploring the links between social-economic inequalities and the burden of non-communicable diseases (Gaspar et al., 2021). It has been an honour and a privilege to share the pursuit of the degree of Doctor of Philosophy with the individuals below.

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● Anthropocene: the current geological epoch, in which humans and societies have become a global geophysical force driving the Earth to change its natural geological epoch – from the Holocene (Steffen et al., 2007). According to Michael Myers: "*By exploiting Earth resources we have a more comfortable existence, and our life spans have increased considerably. But we're now at a tipping point in which the exploitation of the environment is beginning to have a negative impact on human health*" (Seltenrich, 2018).

● Anthropocene risk: according to Keys *et al.* (2019), it describes risks that "*emerge from human-driven processes; interact with global social–ecological connectivity; and exhibit complex, cross-scale relationships*", as complementary approach to systemic risk frameworks. It emphasizes risk framing across all scales (e.g., temporal, spatial, and otherwise). Conceptually, human-induced changes to the Earth system firstly modify the baseline for hazard assessment (for instance, in a changing climate). Second, global social–ecological connectivity modulates exposure and vulnerability, often in highly inequal settings. Third, cross-scale integration can alter how and where risks are predicted and perceived (e.g., short-term or long-term, local or global).

● Burden of diseases: describes death (mortality) and loss of health (morbidity) due to diseases (non-communicable diseases or communicable, maternal, neonatal, and nutritional diseases), injuries (e.g., interpersonal violence, road injuries, or self-harm) and risk factors (environmental and occupational, metabolic, and behavioural risk factors) for all regions of the world (Keating, 2018). By adding together Years of Life Lost (YLL - years of life a person loses as a consequence of dying early because of the disease) and the number of years of life a person lives with disability caused by the disease (YLD –

Years of Life Lived with Disability), it is possible to estimate disease burden as Disability Adjusted Life Year (DALY), in which one DALY represents the loss of one year of life lived in full health.

● Doughnut economics: a model that integrates social and ecological boundaries as interdependent parts of human and planetary wellbeing (i.e., a safe and just space for humanity - Raworth, 2017). Its ecological boundary, defined by the nine Planetary Boundaries framework (Steffen, Richardson, et al., 2015), proposes an ‘ecological ceiling’, beyond which lies an overshoot of pressure to the Biosphere. Its social boundary, composed by twelve dimensions such as health, food, education, and other indicators of minimum standards for human welfare, describes a ‘social foundation’, below which lie shortfalls in wellbeing. The safe and just space for humanity lies between the social foundation and the ecological ceiling.

● Ecosystem multifunctionality: In general, ‘*the ability of ecosystems to simultaneously provide multiple ecosystem functions and services’* (Manning et al., 2018). On this regard, ecosystem functioning is broadly defined as array of biological, geochemical and physical processes that occur within an ecosystem (Manning et al., 2018). Ecosystem services is the contributions that ecosystems make to human well-being – divided into categories of provisioning, regulating, habitat or support, and cultural services (TEEB, 2018).

● Food Systems: all stages of keeping us fed - production, harvesting, processing, manufacture, sales, consumption and disposing of food (HLPE, 2017). A holistic environmental, social, and economic view of all stages, actors and activities involved in these processes, from soil preparation and growing food to its consumption and disposal.

- Inclusive Wealth / Capital goods: a qualifier of wealth that incorporates the sum of produced, human, and natural capitals (Dasgupta, 2021) or, more broadly, the notions of distinct manufactured and financial capitals under produced goods and of an additional social capital. According to Maack and Davidsdottir (2015), "*conventional understanding of capital only includes financial and manufactured (durable) capitals. Skills that are inherent in human resources (human capital) have highly influenced technology development and enhanced societal progress, however today it is often regarded as a company asset in managerial discourse. The concept social capital is emerging as culture and value of trusted interactions that facilitates progress through networking, institutional governance and shared values*". Human capital can be further defined as: the knowledge, skills, competencies and attributes embodied in individuals that facilitate the creation of personal, social and economic well-being (TEEB, 2018). Natural capital has been extensively described as the limited stocks of physical and biological resources found on earth, and of the limited capacity of ecosystems to provide ecosystem services (TEEB, 2018).

- Leverage points: originally proposed by Meadows (1999), these are "*places within a complex system (a corporation, an economy, a living body, a city, an ecosystem) where a small shift in one thing can produce big changes in everything*". Ranked in increasing order of effectiveness, twelve intervention points have been suggested which can be summarised as 'shallow' – relatively easy to implement, with limited effect to the overall system (i.e., parameters and feedbacks) – and 'deep' leverage points – more challenging, less obvious places of intervention, which can potentially bring more meaningful transformation to the system (i.e., design and intent - Abson et al., 2017).

- Lock-in mechanisms: underlying dynamics driven by path dependencies and institutional inertia that influence tipping points that are likely to lead to traps, maladaptation or hinder transformability (Dornelles et al., 2020). Lock-in mechanisms in social-ecological systems incorporate two essential characteristics: reversibility and plausibility to overcome problems.

- Planetary Boundaries: a science-based quantitative risk analysis of anthropogenic pressures on nine different earth systems at the planetary scale: climate change, novel entities, stratosphere ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (Nitrogen and Phosphorus), freshwater use, land-system change, and biosphere integrity - functional diversity and genetic diversity (Steffen, Richardson, et al., 2015). Risks are measured as safe operating space, zone of uncertainty (zone where a threshold is likely to exist) and area of high risk; planetary boundary lays between safe operating space and zone of uncertainty.

- Planetary Health: intended as an inquiry into our total world, it has evolved into a capacious interdisciplinary inquiry that recognises the interdependence between the health of human civilisations and the ecosystems on which they depend (Demaio & Rockström, 2015; Horton, 2018). "*By definition, it explicitly accounts for the importance of natural systems in terms of averted cases of disease and the potential harm that comes from human-caused perturbations of these systems*" (Seltenrich, 2018).

- Resilience: in social-ecological systems, resilience operates through preventive and reactive actions that incorporate the ability to resist or absorb a disturbance, to recover from this stress or shock, to reorganise through adaptation, and to reorient through transformation in order to maintain essential function (Schipanski et al., 2016; Walker et al., 2004). The descriptive concept incorporates insights from engineering, ecological, social-ecological, epistemic, and intersubjective roots (Holling, 1973; Powell et al., 2014).

● Socio-ecological system: defined by Folke *et al.* (2010) as an "*integrated system of ecosystems and human society with reciprocal feedback and interdependence. The concept emphasizes the humans-in-nature perspective*". The foundations of social-ecological systems are a cornerstone for the scholarship of sustainability, revealed by key premises: a) intertwined components: adaptive responses and emergent properties of interactions imply a systemic combination which is bigger than the mere sum of the ecological or the social "parts"; b) cross-scale dynamics: the perception of systemic effects evolves from the interplay between humans and ecosystems at multiple spatial and time scales; c) tipping points: critical thresholds at which small quantitative changes can lead to a fundamentally different system state, beyond the idea of incremental accumulation of individual effects; and d) transforming for change: rather than focusing on potentially insufficient incremental adaptations to intertwined, cross-scale anthropogenic pressures, this notion also proposes breaking down the resilience of one development pathway (i.e., lock-in mechanisms) whilst building alternatives (Dornelles et al., 2020; Reyers et al., 2018).

● Sustainability: capacity to preserve the system in the long-run, as a measure of system performance (Tendall et al., 2015). In this research, sustainability is commonly associated with 'sustainable development': development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). In its essence, sustainable development integrates intergenerational equity with a precautionary principle that enables a synergistic assessment of environmental, economic, and social concerns embedded in decision-making processes.

● Tipping points: refers to a rapid, potentially irreversible transition of a social or ecological system – generally used as analogous to 'regime shifts' or 'critical transition'. Milkoreit *et al.* (2018) proposed a more comprehensive definition of tipping points:

"*…the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible*".

● Transdisciplinary research: according to Lang *et al.* (Lang et al., 2012), it is "*a reflexive, integrative, method driven scientific principle aiming at the solution or transition of societal problems and concurrently of related scientific problems by differentiating and integrating knowledge from various scientific and societal bodies of knowledge*".

● Transformational change: also described as 'transformability', it reveals a fundamentally new stability landscape in a social-ecological system, with different variables in comparison to the old state, such as when a region changes from an agrarian to a resource-extraction economic system (Walker et al., 2004). Synthesized as: "*the capacity to transform the stability landscape itself in order to become a different kind of system, to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable*" (Folke et al., 2010).

● Triple Burden of Malnutrition: the coexistence of undernutrition (e.g., childhood stunting, chronic undernourishment, hunger), excessive forms of malnutrition (e.g., overweight & obesity, diet-related NCDs), and micronutrient deficiency – for instance, anaemia in women of reproductive age, vitamin A deficiency in children (Development Initiatives, 2017).

● Undesirable resilience: with the increased use of 'resilience' as a normative concept, undesirable resilience refers to resilient dynamics in social-ecological systems that reinforce undesirable outcomes for the society and/or the environment (Glaser et al., 2018; Oliver et al., 2018). Undesirable resilience can affect systems by preventing transformation towards a more favourable state or by locking-in systems into unfavourable trajectories. Examples of undesirable resilience are revealed in many forms, such as resilient invasive species, antibiotic resistance, chronic poverty, or terrorist networks (Dornelles et al., 2020).

- BECCS: Bioenergy with carbon capture and storage
- CAPES: Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
- CV: Coefficient of variation
- CTA: Consolidative transformation archetype
- DACCS: Direct air carbon capture and storage
- DALY: Disability Adjusted Life Year
- ETA: Expansionist transformation archetype
- FAO: Food and Agriculture Organization of the United Nations
- IAM: Integrated Assessment Models
- iDiv: German Centre for Integrative Biodiversity Research
- NET: Negative emissions technology
- RETA: Rapidly expansionist transformation archetype
- sDiv: Synthesis Centre for Biodiversity Sciences
- SDG: Sustainable Development Goal
- SES: Social-ecological systems
- UN: United Nations
- WoS: Web of Science
- YLD: Years of Life Lived with Disability

- YLL: Years of Life Lost

Chapter 1: *Introduction*

Chapter 2: *Towards a bridging concept for undesirable resilience in social-ecological systems*

Chapter 3: *Breaking for social-ecological transformations*

Chapter 4: *Transformation archetypes in global food systems*

Chapter 5: *Systemic food risks: synchronised dynamics of shocks to national food availability and supply*

Appendix 1: *Supplementary materials to chapter 1 and 6*

Appendix 2: *Supplementary material to chapter 2*

Supplementary Table 2.5 – Total number of papers published using *resilience, lock-in*, and *undesirable resilience* in their title, abstract, and/or keywords assigned across twenty specific Web of Science research areas between 2000-2018 (contained in Social Sciences and Life Sciences & Biomedicine broad research categories)

Supplementary Figure 2.1 – Diagram of literature analysed according to categorization defined in Web of Science and Scopus databases

Supplementary Figure 2.2 – Standardised number papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Scopus subject areas from 2000 to 18

Supplementary Figure 2.3 – Total number of papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords in Web of Science and Scopus from 2000 to 18

Supplementary Figure 2.4 – Comparison of standardised number of papers published using terms 'resilience', 'lock-in', and 'undesirable resilience' between two broad Web of Science research categories from 2000 to 18: Social and Life Sciences & Biomedicine

Supplementary Figure 2.5 – Quadrant of essential characteristics of 'lock-in' mechanisms: reversibility and plausibility to overcome problems

Appendix 3: *Supplementary material to chapter 3*

Supplementary Table 3.1 – Summary of findings in the four case studies: pollinators decline, Negative Emission Technologies (NETs) fixation, plastic pollution, and meat overconsumption

Appendix 4: *Supplementary material to chapter 4*

Appendix 5: *Supplementary material to chapter 5*

CHAPTER 1

“*An economy predicated on the perpetual expansion of debt-driven materialistic consumption is unsustainable ecologically, problematic socially, and unstable economically*” Tim Jackson; Prosperity without Growth (2009).

INTRODUCTION

Key challenges and opportunities of innovation for humankind over next decades are complexly interconnected and food has a central role to play (Pradyumna, 2018; Rockström et al., 2016). As a species, humans have been transitioning in remarkable pace from being a relatively ‘small world on a big planet’, to a relatively ‘large world on a small planet’ (Rockström et al., 2018). Humanity currently overconsumes resources equivalent to 1.7 Earths to provide the ecosystem services it demands whilst, obviously, there is only one Earth available (Lin et al., 2018). As global food supply chains increase in size, complexity and interconnectivity (Benton & Bailey, 2019; Tilman et al., 2011; Willett et al., 2019), a systemic understanding of the emergent drivers and co-evolving trajectories that can either enable or hinder the transformation of food systems towards more sustainable and resilient directions is sorely needed (Davis et al., 2021; Dornelles et al., 2020; Oliver et al., 2018). As food-related pressures to human and planetary health accumulate (i.e., the interdependence between the health of human civilisations and the ecosystems on which they depend - Demaio & Rockström, 2015; Horton, 2018), so does the risk of transgressing important tipping points (i.e., a rapid, potentially irreversible transition of a social or ecological system to a different state - Milkoreit et al., 2018; Reyers et al., 2018). Thus, time is considerably scarce to: a) develop a refined understanding of the mechanisms which influence the sustainability and resilience of food systems and b) translate such knowledge into practice with tangible actions.

1.1 Food systems

Food systems, from a conceptual perspective, are emblematic of complexity. They can provide essential nutrients and calories for human development and health (Development Initiatives, 2018; UNSCN, 2017); they can be the platform for work and business from local smallholder farmers to massive multinational corporations (FAO, 2017; IFPRI, 2018); they are directly involved with nutrient cycling and ecosystem conversion, for instance, for the expansion and intensification of agriculture (HLPE, 2017; TEEB, 2018); they can regulate the use of primary resources (e.g., freshwater), control the dissemination of pests and diseases (i.e., naturally or chemically), and influence migration patterns of countless animals, including humans (e.g., from the spatial distribution of pollinators to the origins of hunter-gatherer and agricultural communities - TEEB, 2018); they are considerably shaped by cultural traditions, rituals or beliefs (FAO, 2016); and they can also be the leverage point to either start wars and rebellions or to build alliances (FAO, 2017; IFPRI, 2018). From this holistic angle, it is substantially challenging to coherently investigate the dynamic drivers leading to multiple coexistent impacts in food systems (Chaudhary et al., 2018; Zurek et al., 2018), including but not limited to biodiversity loss, land use degradation, food security, greenhouse gases emissions (GHGE), climate extreme events, social-economic inequality, food loss & waste, freshwater scarcity, and more (Development Initiatives, 2018; FAO, 2017; IPCC, 2014; Springmann, Clark, et al., 2018).

Food is a cornerstone for interactions between the United Nations Sustainable Development Goals (UN SDGs – i.e., 17 consensual goals amongst 193 signatory countries designed to end poverty, fight inequality and stop climate change by 2030 - UN, 2015), with key synergies attributed between SDG 2 (zero hunger), SDG 3 (good health and wellbeing), SDG 12 (sustainable consumption and production), and SDG 15 (life on land - ICSU, 2017; Pradhan et al., 2017). Arguably, food systems are the basis that primarily connects SDG 3, SDG 12 and SDG 15 (Pradyumna, 2018) and thus are fundamental for the transformation of social-ecological systems towards sustainable development. Complex interdependent drivers, however, constantly reorient the trajectories of food systems. These include demographic change, scarcity of primary resources, demand for ultra-processed or resource-intensive foods, urbanization, organisation of government structures, power distribution, justice, and equity (Campbell et al., 2017; HLPE, 2017; Klinsky et al., 2017; Klinsky & Golub, 2016; Serraj & Pingali, 2018; Tilman & Clark, 2014; Woodall & Shannon, 2018). Increasingly interconnected food supplies reveal emergent and shared systemic dynamics that exert a crucial role for food systems resilience and sustainability (Davis et al., 2021; Diment et al., 2021; Ingram, 2011). Resilient mechanisms within food systems can either facilitate their resistance, recovery, reorientation, or reorganisation in the direction of sustainable outcomes (Schipanski et al., 2016) or, if biophysical, sociocultural, economic/regulatory or knowledge constraints are persistent, they can hamper sustainable processes and lock-in food systems into unsustainable states or trajectories (Dornelles et al., 2020; Oliver et al., 2018).

Food systems simultaneously provide multiple ecosystem services (i.e., the supply of services relative to their human demand, such as food provision) and functions (i.e., the array of biological, geochemical and physical processes that occur within an ecosystem) – i.e., multifunctionality (Manning et al., 2018). Furthermore, food systems can be the point of convergence of all five capitals (i.e., human, natural, manufactured, financial, and social capitals) for a notion of wealth beyond produced goods (i.e., inclusive wealth - Dasgupta, 2021; Maack & Davidsdottir, 2015). The potential provision of multiple beneficial outcomes from food systems, however, has not been necessarily accomplished:

diets globally tend not to be healthy for humans and they are made available often at the expense of the environment (Afshin et al., 2019; Bahadur et al., 2018; Springmann, Clark, et al., 2018; Tilman & Clark, 2014). Altogether, from the production to the consumption of food lies the potential to substantially (re)shape the direction of human and planetary health for this and for upcoming generations. To better navigate the food problems and opportunities for research and practice, different stages, actors and activities involved in this complex network need to be scrutinized. A ‘food systems’ approach intends to do exactly that.

1.1.1 Conceptual foundations

Food systems, in synthesis, comprise all stages behind the provision of food, livelihoods, and businesses – production, harvesting, processing, manufacture, sales, consumption and disposing of food (HLPE, 2017). It encompasses a holistic environmental, social, and economic view of all stages, actors and activities involved in these processes, from soil preparation and growing food to its consumption and disposal. Stakeholders across food systems stages and activities can be farmers, manufactures, distributors, wholesalers, retailers, food services providers, consumers, governments and/or researchers. An adapted food systems framework is simplified in Figure 1.1 (Nesheim et al., 2015).

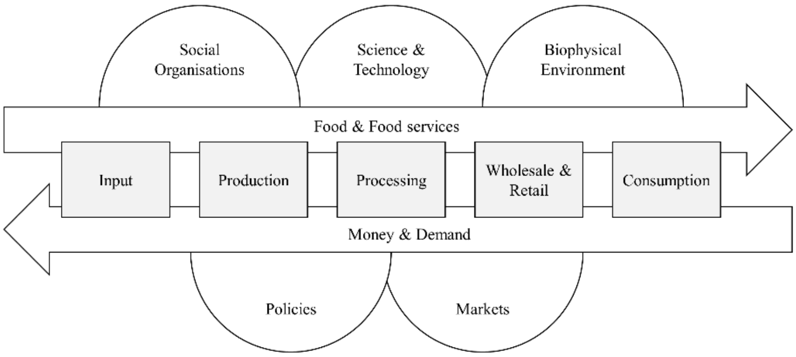

Figure 1.1 – Food systems stages and levels. Navigation across stages of input, production, processing, wholesale & retail, and consumption is driven by food & food services and by money & demand. Each level of food systems is composed by distinct domains and activities: social organisations (education, media, household structure, social movements, and health care system); science & technology (farm inputs, food manufacturing, transport & storage, and medical technologies); biophysical environment (soil, water, climate, plants & animals, nutrients); policies (farm, food & nutrition, labour & trade, environment, health & safety); and markets (food preferences, market structure, competition, global trade, wages & working conditions). Adapted from (Nesheim et al., 2015).

Conceptual frameworks of food systems can vary substantially in terms of size, number of nodes, and complexity (Nicholson et al., 2019). The definition of distinct actors, stages, activities, and interactions in particular frameworks depend fundamentally on the topic of interest from a systemic assessment. In this sense, the simplified framework shown in Figure 1.1 is relevant to describe an overview of stages and levels of food systems, but the illustration, for instance, of the links between food security, the environment, and social welfare requires more detailed conceptual models (Ingram, 2011) or extensive global food systems maps (ShiftN., 2009). A key characteristic shared across frameworks of food systems lies in the acknowledgement of the interconnections between, across and within multiple stages, actors, drivers and outcomes from a range of viewpoints (HLPE, 2017). The concept of a food system, therefore, operates as an autopoietic system, which reproduces itself from within itself (Seidl, 2004), with dynamic interactions in the presence of perturbations and transformations (Schipanski et al., 2016), and reveals non-linear mutations and considerable degrees of unpredictability.

A ‘food systems’ approach explicitly takes into consideration the fact that human health and human civilization depend on flourishing natural systems and adequate management of resources (i.e., a notion of social-ecological systems - Reyers et al., 2018). Understanding the dynamics within food systems is particularly relevant under the challenges presented by the Anthropocene, the new geological epoch characterised by human pressures causing incremental global environmental risks and, for the first time, humans constitute the prime driver of planetary change (Steffen et al., 2007; Steffen, Broadgate, et al., 2015). Global social-ecological connectivity modulates the exposure and vulnerability to human-driven process, exhibiting complex, cross-scale relationships (i.e., Anthropocene risks - Keys et al., 2019). In the presence of potential synergies and feedbacks between nodes of a system, or positive and negative feedback loops within links of systemic components, enquiries of sustainability and resilience of food systems become inherently multifaceted.

1.1.2 Sustainability and resilience in food systems

The era of Sustainable Development can be tracked back to the Brundtland Report, which presented its the cornerstone definition: "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). The United Nations (UN) incorporated the "Three Pillars of Sustainability": Economy, Society and Environment. After the Millennium Development Goals (MDGs) by 2015, 193 global leaders agreed to the Sustainable Development Goals (SDGs) and redefined 17 global goals to achieve three outstanding milestones: end poverty, fight inequality and stop climate change by 2030 (UN, 2015). In its essence, the notions of sustainability and of sustainable development integrate intergenerational equity with a precautionary principle that enables a synergistic assessment of environmental, economic, and social concerns embedded in decision-making processes.

Commonly used complementarily to the concept of sustainability, resilience has gained traction to describe the ability to resist or absorb a disturbance (i.e., robustness), to recover from a stress or shock, to reorganise through adaptation, and to reorient through transformation in order to maintain essential functions (e.g., provision and distribution of food in food systems - Diment et al., 2021; Schipanski et al., 2016; Walker et al., 2004). Both notions of sustainability and resilience are accompanied by important questions for their valuable assessment: of what (e.g., food production or availability), for whom (e.g., for farmers or citizens), and at what time scale (e.g., annual or decadal - Helfgott, 2018). In addition, it is relevant to ask ‘to what’ resilience is applied (e.g., to pests or to climate shocks - Diment et al., 2021). The interdisciplinary foundations, applications, and ramifications of the concept of resilience have been developed in more detail in Chapter 2 of this thesis.

The concepts of sustainability and resilience have coevolved with more comprehensive analytical and practical values in parallel with insights of social-ecological systems dynamics. A social-ecological systems can be summarised as an “*integrated system of ecosystems and human society with reciprocal feedback and interdependence*”, emphasizing a humans-in-nature perspective (Folke et al., 2010). The foundations of social-ecological systems are a cornerstone for the scholarship of sustainability, revealed by key premises: a) intertwined components: adaptive responses and emergent properties of interactions imply a systemic combination which is bigger than the mere sum of the ecological or the social “parts”; b) cross-scale dynamics: the perception of systemic effects evolves from the interplay between humans and ecosystems at multiple spatial and time scales; c) tipping points: critical thresholds at which small quantitative changes can lead to a fundamentally different system state, beyond the idea of incremental accumulation of individual effects; and d) transforming for change: rather than focusing on potentially insufficient incremental adaptations to intertwined, cross-scale anthropogenic pressures, this notion also proposes breaking down the resilience of one development pathway whilst building alternatives (Reyers et al., 2018). The evolution of the concept of ‘tipping points’ is more specifically elaborated in Chapter 2 of this thesis, whilst the foundations and operationalisation of the concepts of ‘transformation’ and ‘leverage points’ (i.e., places in a system where a small shift in one part can produce important systemic changes) are further discussed in Chapter 3.

Some conceptual models can help to translate the premises of sustainability and/or resilience into a tangible perspective of social-ecological systems. The ‘Planetary Boundaries’ model (Steffen, Richardson, et al., 2015), for instance, aims to quantify risks associated to anthropogenic pressures on nine different earth systems at the planetary scale: climate change, novel entities, stratosphere ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (Nitrogen and Phosphorus), freshwater use, land-system change, and biosphere integrity (quantified as functional diversity and genetic diversity). In a complementary manner, the ‘Doughnut economics’ model integrates social and ecological boundaries as interdependent parts of human and planetary wellbeing (i.e., a safe and just space for humanity - Raworth, 2017). Its ecological boundary, defined by the nine Planetary Boundaries framework, proposes an ‘ecological ceiling’, beyond which lies an overshoot of pressure to the Biosphere. The safe and just space for humanity lies between the social foundation and the ecological ceiling.

Building from the Planetary Boundaries and the Doughnut economics models, a food systems conceptual model (with distinct hierarchical levels, multiple dimensions across levels, interdependent drivers, diverse stages from production to consumption, and interrelated activities across stages) is illustrated in Figure 1.2. This conceptual framework aims to be a simplified yet not simplistic illustration; a comprehensive but not overwhelming display of dynamic interactions across food systems stages, drivers, and domains. Note that the appropriateness of conceptual frameworks depends fundamentally on the general objectives of a particular research problem and study design. Thus, more restrictive models are arguably more appropriate to examine, for instance, the links between national stability of crops output and diversity of individual crops within the production stage (Renard & Tilman, 2019), whilst the investigation of environmental effects from the international trade flow of agricultural commodities from a perspective of companies requires more refined models and parameters between production, supply chain, and consumption (Ermgassen et al., 2020).

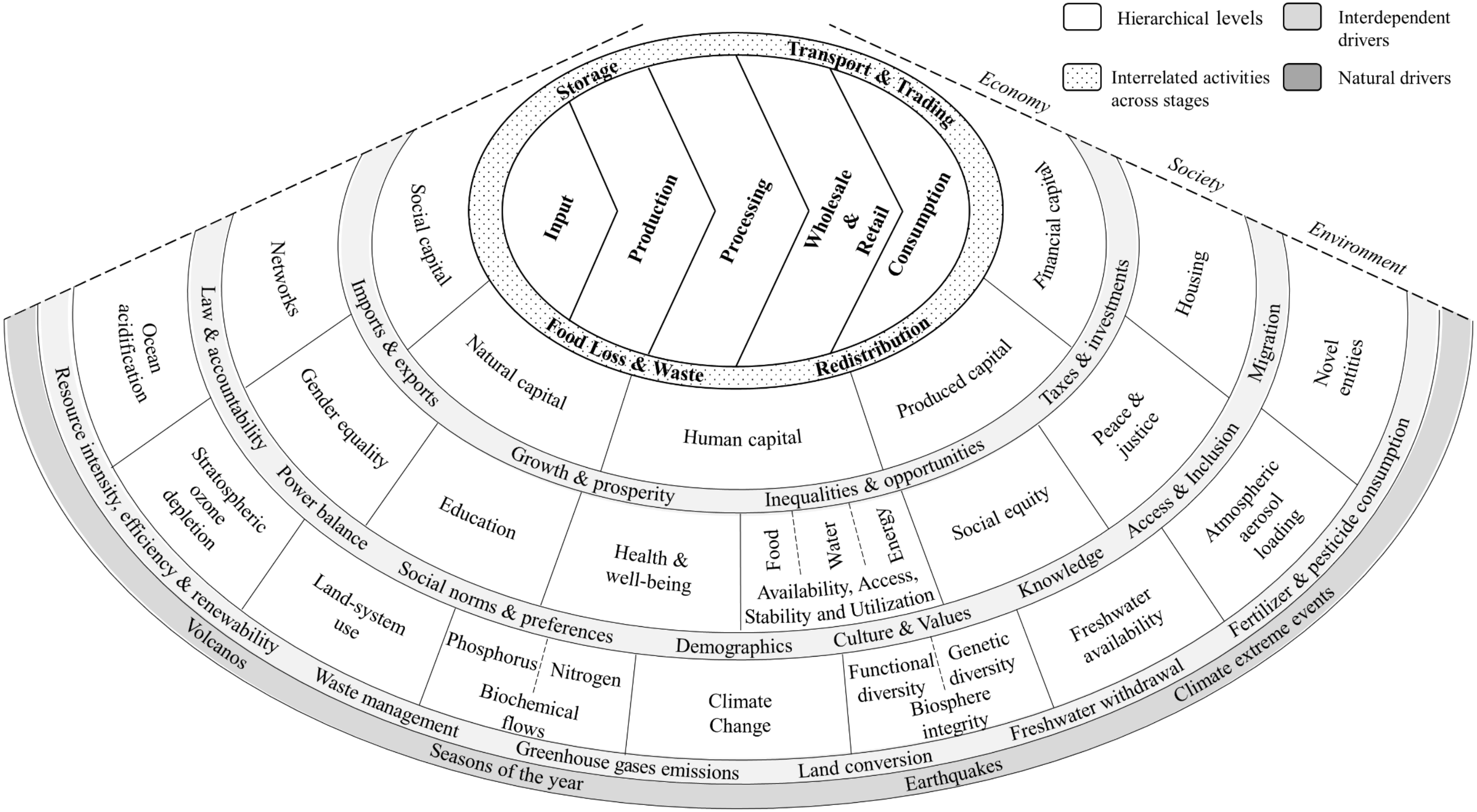
Hierarchical levels
Interdependent drivers
Interrelated activities across stages
Natural drivers
Economy
Society
Environment
Storage
Transport & Trading
Input
Production
Processing
Wholesale & Retail
Consumption
Food Loss & Waste
Redistribution
Social capital
Financial capital
Natural capital
Human capital
Produced capital
Imports & exports
Growth & prosperity
Inequalities & opportunities
Taxes & investments
Networks
Housing
Gender equality
Education
Health & well-being
Food
Water
Energy
Availability, Access, Stability and Utilization
Social equity
Peace & justice
Law & accountability
Power balance
Social norms & preferences
Demographics
Culture & Values
Knowledge
Access & Inclusion
Migration
Ocean acidification
Stratospheric ozone depletion
Land-system use
Phosphorus
Nitrogen
Biochemical flows
Climate Change
Functional diversity
Genetic diversity
Biosphere integrity
Freshwater availability
Atmospheric aerosol loading
Novel entities
Resource intensity, efficiency & renewability
Waste management
Greenhouse gases emissions
Land conversion
Freshwater withdrawal
Fertilizer & pesticide consumption
Volcanos
Seasons of the year
Earthquakes
Climate extreme events

Figure 1.2 (continued from previous page) – Hierarchical levels and interdependent drivers across food systems stages and dimensions. The operational level illustrates the food systems stages (i.e., input, production, processing, trade, wholesale & retail, and consumption) and interrelated activities across each stage (i.e., storage, transport & trading, food loss & waste, and redistribution). The three hierarchical levels and their respective dimensions are displayed in order: economy (i.e., diverse types of capital), society (i.e., safe and just space for food security), and environment (i.e., nine planetary boundaries). Multiple interdependent drivers express human-induced factors which pressure their subsequent levels collectively. Natural drivers demonstrate inherent forces which influence the resilience and sustainability of food systems. Note: this figure does not explicitly illustrate outcomes of food systems (e.g., malnourishment, or crop yields), which lie within the multiple levels, stages, and dimensions.

For a holistic understanding of the anatomy of food systems and the links to sustainability and resilience, there are two key characteristics that distinguish the framework of Figure 1.2 in comparison to others described in the literature: a) a hierarchical relationship across levels, and b) the existence of interdependent drivers. The activities of every actor (e.g., an individual, a company, or a country) engaging in food systems affects, directly or indirectly, at least one domain in each of the hierarchical levels (those being, the environment, the economy, and the society). The domains of this framework are a non-exhaustive list of relevant boundaries within environment, society, and economy levels, which are commonly expressed as a measurable ‘outcomes’ (e.g., food security under ‘availability, access, stability, and utilization’ of food, water, and energy resources; nitrogen concentration from synthetic fertilizers use under biogeochemical flows; or simply monetary gains under produced capital - Campbell et al., 2017; FAO et al., 2020; OECD-FAO, 2019). This framework explicitly expands on notions of overlapping horizontal ‘pillars’ (e.g., the three pillars of sustainability - WCED, 1987) which necessarily follow a hierarchical relation for their functionality: a first tier represented by the environment, a second tier of society, and a third tier of the economy. In simple terms, there is no society without an environment, there is no economy without a society, and hence there are no food systems without the three embedded economy, society, and environment levels (IOM & NRC, 2015; Reyers et al., 2018). In this sense, the red area in the economy pilar, outside the ‘viable’, ‘equitable’, and ‘sustainable’ areas (Supplementary Figure 1.1 – Appendix 1), is an abstraction that simply does not exist in an empirical sense, as an environment and a society are necessary conditions for its existence. This hierarchical relationship illustrated in the model of Figure 1.2, therefore, helps to explicitly clarify the misconception around the concept of ‘externalities’: our anthropogenic operational and functional systems (e.g., food, energy, transport or others) are, fundamentally, embedded within nature, not merely applied to it – and certainly not external to it (Dasgupta, 2021).

The second characteristic of the model in Figure 1.2 relates to the interdependence of drivers in terms of their vertical relationship (i.e., across hierarchical levels), aiming to represent the presence of positive or negative effects and potentially feedback loops across levels. It expands the notion of interactions between levels and domains beyond single influences (a → b; i.e., from a to b), revealing explicit coexistent parameters that drive quantitative or qualitative changes in multiple directions jointly (e.g., simultaneous pressures driven by waste management, greenhouse gases emissions, demographic change, and imports & exports). These interactions mainly reveal anthropogenic pressures across levels and domains of food systems (e.g., demographic changes in society, such as population growth and urbanization, leading to increased demand for expansion of the land-use systems in the environment; or formalised networks of infrastructure facilitating the flow of exports between agricultural commodity producers and food manufacturers in different nations). Note that the effect of one or many the interdependent drivers in distinct domains across levels is dependent on the emergence from their dynamic interactions due to the existence of feedback loops (Davis et al., 2021; Reyers et al., 2018), so it is important not to artificially deconstruct intertwined aspects of social-ecological systems into a mere sum of the ecological, social, or economic “parts” (Reyers et al., 2018). In this sense, interdependent drivers incorporate premises of cross-scale dynamics beyond incremental accumulation of individual effects which, in combination, are relevant to illustrate the idea of critical thresholds at which small quantitative changes can lead to fundamental changes to the system (i.e., tipping points, sensitive interventions, and leverage points - Abson et al., 2017; Farmer et al., 2019; Milkoreit et al., 2018).

Whilst the sustainability and resilience of food systems are often described as desirable goals in the normative sense (Biggs et al., 2015; Schipanski et al., 2016), it is paramount to acknowledge that the same intertwined dynamics and properties within systems can lead to alternative, unexpected, and often undesirable outcomes. The emergence of resilient proprieties which maintain undesirable systems proprieties (e.g., poverty traps leading to persistent hunger, or rising climate shocks creating unsustainable conditions for stable food production) can prevent transformation towards a more favourable state(s) or lock-in systems into unfavourable trajectories (Haider et al., 2018; Oliver et al., 2018). Such phenomena are described in this thesis as lock-in mechanisms, linking sustainability, resilience, and transformation with a problem-oriented agenda. The persistence of resilient dynamics within intertwined properties, parts or levels of a system leading to undesirable outcomes in terms of sustainability for the environment and/or for society is relatively unexplored in the literature (Dornelles et al., 2020; Glaser et al., 2018).

1.1.3 Relevance for research and practice:

Intense demographic change and expected impacts from anthropogenic climate change over the next decades are expected to intensify the competition for increasingly scarce land, water and food resources (IPCC, 2014; Steffen, Broadgate, et al., 2015; UN DESA, 2017; Whitmee et al., 2015). These impacts tend to disproportionally affect communities least responsible for GHGE and those that are most vulnerable in society (Klinsky et al., 2017). If insufficient mitigation persists, these undesirable effects are anticipated to increase in developing countries and coastal regions, followed by expanded urbanization and increased dietary intake of resource-intensive protein sources and ultra-processed foods (M. E. Brown et al., 2015; IPCC, 2014; Tilman & Clark, 2014; UN DESA, 2015). These patterns are expected to influence the triple burden of malnutrition (i.e., coexistence of hunger, overweight, and micronutrient deficiency) and the burden of disease (i.e., mortality and morbidity due to diseases, injuries, and risk factors) of global populations in a complex manner. Paradoxically, increasing hunger (i.e., insufficient dietary energy consumption required to maintain a normal active and healthy life) is simultaneously being recorded in parallel to an important rise in people affected by non-communicable diseases, mostly associated or caused by the global burden of malnutrition, altogether influenced by and inducing further social, environmental and economic preventable problems in this multi-stakeholder vicious cycle (Development Initiatives, 2017; IFPRI, 2016; IMF, 2017; IPCC, 2018). The mainstream food research agenda, however, mostly focuses on food production (especially crops) and consumption in isolation, and does not pay due attention to the feedback cycles and synergies present in food systems (Campbell et al., 2016; Development Initiatives, 2017; Gundimeda et al., 2018).

Agriculture, a key stage of production in food systems covering approximately 43% of the world's ice- and desert-free land, is responsible for 61% of food's GHGE (81% including deforestation), 79% of acidification, and 95% of eutrophication (Poore & Nemecek, 2018). In addition, agriculture is the major driver of transgression of planetary boundaries in comparison to other socio-ecological systems - out of nine planetary boundaries, two have been fully transgressed and three are in the zone of uncertainty(Campbell et al., 2017; Steffen, Richardson, et al., 2015). Alarmingly, environmental pressures from food systems are expected to increase by 2050 87% for GHGE, 67% for cropland use, 54% for phosphorus application, and 51% for nitrogen application, based on current trajectories (Springmann, Clark, et al., 2018). Even based on ambitious scenarios of synergistic combination of dietary, technological, and food loss & waste change under an optimistic income and population growths, it will be considerably challenging to keep food systems within planetary boundaries in the near future (Springmann, Clark, et al., 2018). Therefore, a comprehensive understanding of the embedded lock-in mechanisms that prevent transformation towards more favourable states or that lock-in food systems into unsustainable trajectories is sorely needed.

1.2 Lock-in mechanisms in food systems: linking resilience, sustainability, and transformational change.

Past decades have been accompanied by tremendous progress for humanity worldwide: the absolute number of people living in extreme poverty status declined from 2.2 billion in 1970 to 706 million in 2015 (World Bank, 2018), life expectancy has grown 23 years for women (53 – 76) and 22.5 years for men (48 – 71) between 1950 and 2017 (Dicker et al., 2018), whilst the prevalence of hunger decreased from around 13% to 9% (roughly 825 and 690 million people, respectively) between 2005 and 2019 (FAO et al., 2020).

The measurement of progress for these and for other outcomes of wellbeing, nonetheless, are not always computed in terms of the inputs needed for such achievements nor with respect to damages cogenerated in the process (commonly described as externalities - Dasgupta, 2021). In this sense, without the appropriate evaluation of intended and non-intended procedural trade-offs, this perception of progress of seemingly desirable outcomes fails to provide valuable insights for important domains of sustainability or systemic efficiency. This is particularly relevant for global food systems (IPES-Food, 2016), for instance, on its capacity to nourish people with healthy and sustainable diets per unit input (Benton & Bailey, 2019).

Increased demand for animal protein has led to livestock dominating 83% of the world's farmland and contributing to 58% of food's greenhouse gases emissions despite providing merely 37% of proteins and 18% of calories for human consumption. Simultaneously, feed has driven 67% of agriculture's deforestation (Poore & Nemecek, 2018). Increased crop yields have led to food prices declining which, in parallel, were accompanied by an increase of food loss & waste and GHGE from food production (Benton et al., 2018; Porter et al., 2016; Tilman & Clark, 2014). Despite tremendous increase in food production, agricultural systems fail to deliver nutritional recommendations of protein, vegetable and fruits, whilst sugar, oils & fats and whole grains are over-produced (Bahadur et al., 2018). Furthermore, the attainment of modest progress in some of the SDGs has come at the expense of planetary boundaries being severely transgressed (Collste et al., 2018). Considering how interconnected challenges in the food sector are (Oliver et al., 2018), inefficient progress can further increase risks and impair resilience of an already fragile context – particularly worrisome in the presence of drivers such as demographic change and climate change. Food systems, in this sense, are arguably locked into unsustainable trajectories of systemic inefficiencies

(Figure 1.3) and, if inertia is not replaced by ambitious transformational change, patterns of overexploitation and risk are expected to grow (Collste et al., 2018; Springmann, Clark, et al., 2018).

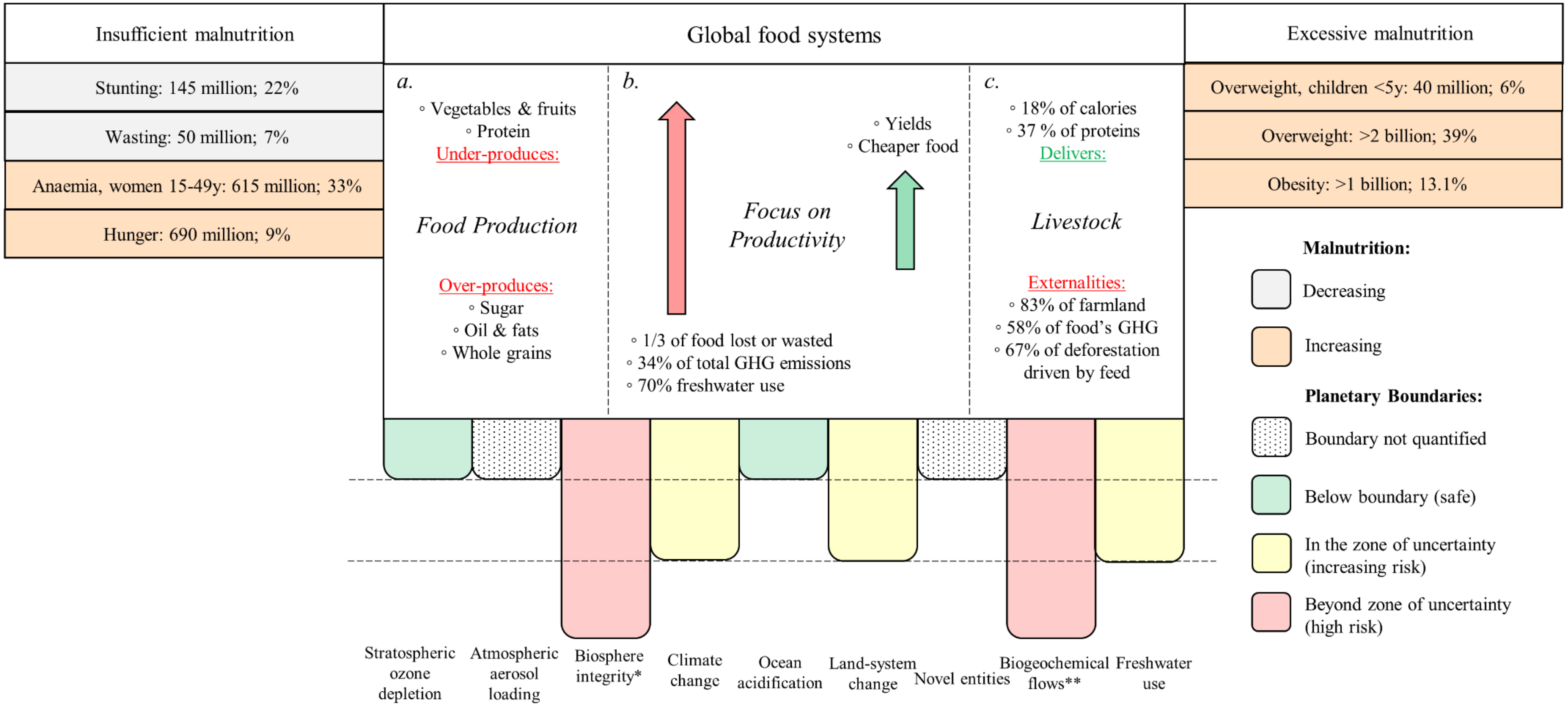

Figure 1.3 – Food-related impacts to human and planetary health. Three examples of inefficient practices in food systems are shown (centre of the figure): a) inadequacy between global food production and human nutritional needs (Bahadur et al., 2018); b) discrepancies between the benefits of increased yields and the undesirable consequences of increasing production (Benton & Bailey, 2019; Crippa et al., 2021; Porter et al., 2016; Tilman & Clark, 2014); and c) relation between input of resources and output of nutrients in livestock production (Poore & Nemecek, 2018). The role of agriculture as a driver of transgression of planetary boundaries is displayed (bottom of the figure), in particular to (*) genetic diversity and to (**) Phosphorus and Nitrogen sources beyond zone of uncertainty (Campbell et al., 2017). Increasing and/or decreasing prevalences of malnutrition are shown at the top right and top left of the figure (FAO et al., 2020).

Global societies and multiple socio-ecological systems are interlocked into a high-carbon global economy by many factors: energy-intensive infrastructures, infinite growth ideology, high-consumption culture, and concentration of power (Simms & Newell, 2017). Dynamic interactions between path dependency, institutional inertia and systemic tipping points are likely to lead to traps, maladaptation, or hinder transformability (Dornelles et al., 2020), while transformation is often merely mentioned as a metaphor in the literature (Feola, 2015) – more details on the links between lock-ins and transformation are explored in Chapter 3 of this thesis. Due to path dependency, the longer a socio-ecological system is locked into trajectories of inefficient and unsustainable progress, the harder it may be for transformational change to occur. For instance, efforts to decarbonise our economy are not yet strong enough to overcome growing global energy needs (Le Quéré et al., 2018). If explicit cooperation to tackle GHGE had started in 2000, only 4% reduction per year would be required – in comparison to more challenging 18% at present (Le Quéré et al., 2018). Similarly, the longer universal health care is delayed, the more expensive it gets (Development Initiatives, 2018). Ultimate examples of undesirable resilience leading to problems which are often difficult, costly, or even impossible to reverse have been documented in many social-ecological system: coral reefs, marine systems, dryland systems, agroecosystems, and artic systems (Reyers et al., 2018). Therefore, lock-in mechanisms ideally must be identified as early as possible to enhance the plausibility to overcome complex challenges.

1.3 How can this PhD advance food systems scholarship?

The general aim of my PhD research is to investigate different mechanisms that ‘lock-in’ food systems into unsustainable pathways, and evaluate how these mechanisms vary between countries from an interdisciplinary angle. In this thesis, each manuscript can advance the food systems scholarship with particular distinctions, more specifically described below:

- Manuscript 1: based on a research design of literature analysis, this study qualified, quantified, and compared concepts of desirable and undesirable interpretations of resilience across multiple academic disciplines and aimed to find a term with potential to contribute to a common understanding. With a group of collaborators from diverse backgrounds, we were able to identify an integrative understanding (i.e., bridging concept) around the term 'lock-in'. A bridging concept can integrate insights and methodologies across disciplines contributing to sustainability science, can improve the consistency of resilience thinking as a complementary concept, and thereby enable a more comprehensive exploration of social-ecological dynamics towards more sustainable futures.
- Manuscript 2: designed as a perspective piece of evidence synthesis, this study aimed to operationalize a methodological understanding between the undesirable properties of resilience (lock-ins) and their impacts on transformations towards sustainability in four case studies. This analysis reveals 'enabling conditions' – sharing common elements with multiple lock-ins (inter-locked mechanisms) – that can bring synergistic benefits for sustainability transformation across different social-ecological challenges. Understanding enabling conditions can provide meaningful insights to successfully crack persistent lock-in mechanisms across diverse endeavours to sustainable development.
- Manuscript 3: this study was a quantitative assessment of empirical and longitudinal rates of change across 161 national food systems. This approach specifically captured the transformational feature of food systems, as it aimed to identify the similarity of transformations across and within multiple countries

under a comparable methodology. Our model underscores the importance of quantifying the multiple human and environmental dimensions of food systems transformations to identify potential leverage points for sustainability transformations. Our analysis shows that under current trajectories of change, “business-as-usual” propositions or “incremental-adaptation” initiatives focusing on higher yields alone are not only insufficient to achieve consensual global goals (e.g., ending hunger or limiting global warming to 1.5°C - Pradhan et al., 2017) but they could even hamper the attainment of other goals indirectly (e.g., health system costs for reasonable prevention and treatment of diet-related non-communicable diseases - Development Initiatives, 2020).

- Manuscript 4: this study aimed to quantify networks of 151 countries and identify synchronised dynamics in terms of interannual fluctuations and shocks in dietary energy supply and food supply of crops and livestock from 1961 to 2013. The model used in this study provides an empirical description of dynamic and shared patterns of interannual fluctuations across increasingly interconnected global food networks. From a systemic risk perspective, we argue that this approach can reveal emergent and simultaneous shock patterns in dietary energy supply and food supply. Our model enables an investigation of changes over time in diverse food groups and multiple stages of the food system simultaneously (i.e., beyond consumption or production in isolation) and is thus relevant to identify increasingly interconnected patterns across countries and inform food security strategies.

Collectively, this thesis aims to research a link between resilience, sustainability, and transformational change in food systems from an interdisciplinary and holistic perspective.

1.4 Structure of the thesis

This thesis is composed by a collection of papers, detailed below:

- Introduction (chapter 1)
- Manuscript 1 (chapter 2) – Towards a bridging concept for undesirable resilience in social-ecological systems.
- Manuscript 2 (chapter 3) – Breaking lock-ins for social-ecological transformations.
- Manuscript 3 (chapter 4) – Transformation archetypes in global food systems.
- Manuscript 4 (chapter 5) – Systemic food risks: synchronised dynamics of shocks to national food availability and supply.
- Conclusions & reflections (chapter 6).

TOWARDS A BRIDGING CONCEPT FOR UNDESIRABLE RESILIENCE IN SOCIAL-ECOLOGICAL SYSTEMS

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2.1 ABSTRACT

Resilience is an extendable concept that bridges the social and life sciences. Studies increasingly interpret resilience normatively as a desirable property of social-ecological systems, despite growing awareness of resilient properties leading to social and ecological degradation, vulnerability or barriers that hinder sustainability transformations (i.e., ‘undesirable’ resilience). This is the first study to qualify, quantify and compare the conceptualization of ‘desirable’ and ‘undesirable’ resilience across academic disciplines. Our literature analysis found that various synonyms are used to denote undesirable resilience (e.g., path dependency, social-ecological traps, institutional inertia). Compared to resilience as a desirable property, research on undesirable resilience is substantially less frequent and scattered across distinct scientific fields. Amongst synonyms for undesirable resilience, the term lock-in is more frequently and evenly used across academic disciplines. We propose that lock-in therefore has the potential to reconcile diverse interpretations of the mechanisms that constrain system transformation – explicitly and coherently addressing characteristics of reversibility and plausibility – and thus enabling integrative understanding of social-ecological system dynamics.

2.2 Introduction

‘*Resilience*’ is a transdisciplinary concept used across the environmental, social, economic, political, and health sciences. The concept refers to preventive and reactive capacities to resist or absorb a disturbance, to recover from stress or shocks, to reorganise through adaptation, and to reorient through transformation in order to maintain essential functions (Chapin et al., 2010; Folke et al., 2010; Walker et al., 2004). Resilience also cultivates the ability to persist and “…*sustain development in the face of change, incremental and abrupt, expected and surprising*” (Folke, 2016, p. 7). The concept is useful to: 1) explore dynamic transformational change of social-ecological systems (SES) needed for earth stewardship in the Anthropocene (Folke et al., 2010; Reyers et al., 2018); and 2) combine and complement various scientific paradigms into a working synthesis needed for sustainability science (Bettencourt & Kaur, 2011; Hediger, 1999).

As a descriptive concept, *resilience* incorporates insights from engineering, ecological, social-ecological, epistemic and intersubjective roots (Holling, 1973). How to define or measure *resilience* can vary widely across these perspectives (e.g., the notion of ‘equilibrium’ is considerably different between engineering and social-ecological narratives - Powell et al., 2014; Weise et al., 2020). As its use across academic disciplines has expanded and been refined for interdisciplinary collaboration over the years (Gao et al., 2016; Tu et al., 2019), so has its implicitly normative use (e.g., aims of ‘building resilience’ - Biggs et al., 2015), especially in the translation of scientific work to policy and practice (Davoudi et al., 2012) and/or to transdisciplinary applications where scientific knowledge is co-created with stakeholders from various sectors (Lang et al., 2012). In other words, in parallel to its framing as a descriptive concept across disciplines (and beyond arguments of how to measure ‘stable’ or ‘dynamic’ properties), *resilience* has been continually reported as a desirable quality in a positive-normative fashion:

ranging from resilient food systems (Schipanski et al., 2016), climate resilient societies (James et al., 2014), to resilient governmental institutions (Folke et al., 2002). The use of the concept in this manner can create inconsistencies around the nature of analysing *resilience* (i.e., scientific concepts are not supposed to be inherently normative) and reveal inevitable debates around normative assumptions: every 'good' or 'desirable' quality has its 'bad' or 'undesirable' flip-side.

While building and maintaining *resilience* of SES is often seen as a key activity to achieve sustainability (Biggs et al., 2015), there is increasing recognition of resilient properties in some systems that '*lock-in*' unfavourable regimes thereby preventing transformation towards a more favourable state (Haider et al., 2018; Phelan et al., 2013; Standish et al., 2014), or that '*lock-in*' systems into unfavourable trajectories. We refer to this kind of resilience as '*undesirable resilience*' on the basis that it leads to the persistence of undesirable outcomes (cf. Oliver et al., 2018). The concept refers to resilient dynamics within intertwined properties, parts or levels of a system leading to undesirable outcomes in terms of sustainability for the environment and/or for society (Glaser et al., 2018).

The use of *undesirable resilience* explicitly reveals its often implicit normativity, and therefore the different goals and interests actors might have. *Resilience* that is desirable for one may be undesirable for others (Helfgott, 2018). Furthermore, elements of time and scale are also relevant for understanding the undesirability of resilience (Weise et al., 2020): focusing on short-term benefits can undermine long-term desirable outcomes (Oliver et al., 2018) and prioritizing only local or global scales can impair the assessment of cross-scales interconnectedness (Reyers et al., 2018), even with an aim of overall benefits to wider society (e.g., the framing of the UN Sustainable Development Goals). Therefore, to ensure clear communication and to facilitate collaboration across disciplines, it is essential to critically analyse the concepts being referred to, distinguishing desirable and undesirable aspects of resilience, and the normative assumptions ascribed to them in the resilience literature.

Scholars currently use a number of different terms to describe *undesirable resilience* such as: ‘*path dependency’* (Mahoney, 2000; Pierson, 2000), ‘*institutional inertia’* (Rosenschöld et al., 2014), ‘*maladaptation’* (Barnett & O’Neill, 2010; Juhola et al., 2016), ‘*unhelpful resilience’* (Standish et al., 2014), ‘*perverse resilience’* (Phelan et al., 2013), and more (Box 2.1). However, these terms appear to be tied to disciplinary narratives; their use and meaning have not been compared between disciplines, leading to potential miscommunication or inaccurate application in inter- or transdisciplinary research. Here we seek to quantify the extent to which the synonyms of undesirable resilience are used across multiple scientific fields in order to allow cooperation without explicit consensus (i.e., as a boundary object - Brand & Jax, 2007) or to actively link disciplines and stimulate dialogues between scientific and political realms (i.e., as a bridging concept - Davoudi et al., 2012).

Box 2.1 – Definitions and use of synonymous of undesirable resilience.

Undesirable resilience: Resilience of aspects of a system that reinforce undesirable outcomes for society (Oliver et al., 2018). For example, maintaining the economic resilience of global, modernised food supply chains often entails large-scale land acquisition by multinational private interests (to secure production across multiple territories to defray risks from extreme weather events, financial crashes or conflicts), but this can exacerbate and make more resilient undesirable outcomes for small farmers and local communities (e.g., biodiversity loss, food insecurity and power exclusion (EEA, 2015). Other proposed examples are resilient invasive species, antibiotic resistance, chronic poverty, and concentration of power (IPES-Food, 2016).

Path dependency: According to Mahoney (2000) path dependency refers to “…*historical sequences in which contingent events set into motion institutional patterns or event chains that have deterministic properties*” (p. 507). A narrower perspective suggested by Pierson (2000) sees it as a social process grounded in a dynamic of ‘increasing returns’, whereby “*preceding steps in a particular direction induce further movement in the same direction*” (p. 252). Increasing returns preserve and reinforce structures and practices required to keep a system intact and functioning, thereby impairing local or regional transformation or innovation and enhancing power asymmetries (Hassink, 2005). Modern industrial agriculture, for example, requires specialized machinery, inputs and networks in order to see the return of these investments, to spread the costs of production and to achieve competitive prices (IPES-Food, 2016).

Institutional inertia: According to Rosenschöld *et al.* (2014), institutional inertia can be understood as "*…the tendency of institutions within the political arena to resist change and thereby stabilize policy"* (p. 639). Different mechanisms can generate and regenerate institutional inertia: costs, uncertainty, path dependency, power, and legitimacy. Termeer *et al.* (2018), for example, demonstrated the extension of institutional inertia in South African fragmented government structures, which persisted excluding the people most affected by food insecurity despite ambitious objectives of governance arrangements. Additionally, 'stickiness' of institutions to move slowly or resist change can impair international partnership needed for the Sustainable Development Goals (SDG number 17), especially the persistence of policy disconnects among countries (e.g., unsustainable agricultural subsidies and land use reforms - IAP, 2018).

Lock-in: Lock-in occurs through a combined process of "*technological and institutional co-evolution driven by path dependency increasing returns to scale*" (p. 817 - Unruh, 2000). Lock-in mechanisms can be characterised in terms of plausibility to overcome them and their reversibility (Supplementary Figure 2.5 – Appendix 2). We suggest an integrative definition of lock-in mechanisms: **dynamic interactions between social-ecological drivers and tipping points that are likely to lead to traps, maladaptation or to hinder transformational change towards sustainability**.

Perverse resilience: Perverse resilience refers to "*resilience within a system that is undesirable to the extent that it is socially unjust, inconsistent with ecosystem health or threatens overall system viability*" (p. 202 - Phelan et al., 2013). The concept unveils social norms and power relations in relation to the dynamic of social-ecological systems by linking concepts of resilience and hegemony. Perverse resilience of the coal industry interested in maintaining coal dependency in Australia, for example, has influenced labour unions and governments and led to ineffective policies and action responses designed to halt anthropogenic climate change (Evans, 2008).

Social trap: The term refers to the conjuncture of factors that enhance vulnerabilities. The term is broadly defined and as such applied across a number of social disciplines. Most research on social traps focus on poverty traps, defined as historical and cultural lack of opportunities and capacities that reinforce a life below certain assets threshold (Barrett & Swallow, 2006). Additionally, chronic poverty, path dependency and lock-ins are suggested to be types of traps across disciplines and share common characteristics: persistence, undesirability, and self-reinforcement (Haider et al., 2018).

Maladaptation: A term suggested by Barnet & O'Neill (2010) as "*action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups*" (p. 211). It has been further developed by Juhola *et al.* (2016) who wanted to use the concept to understand political outcomes: "*a result of an intentional adaptation policy or measure directly increasing vulnerability for the targeted and/or external actor(s), and/or eroding preconditions for sustainable development by indirectly increasing society's vulnerability*" (p. 135). Maladaptive outcomes can be summarized in three types: rebounding vulnerability, shifting vulnerability and eroding sustainable development.

Social-ecological trap: Social-ecological traps refer to complex interactions between social and environmental factors, such as environmental degradation, exposure to violence, or poor sanitary conditions that reinforce vulnerabilities (Boonstra & de Boer, 2014). In comparison to social traps, the term integrates insights from development economics and sustainability sciences, incorporating four additional characteristics: cross-scale interactions, path dependencies, the role of external drivers, and social-ecological diversity (Haider et al., 2018). Trap dynamics, low connectedness, and low resilience of a social-ecological system can all lead to social-ecological traps.

Unhelpful resilience: The term refers to the resilience of an ecosystem to a disturbance that impedes the return to a pre-disturbance state without assistance (Standish et al., 2014). The term helps to understand thresholds of disturbance in ecosystem management and to support whether or not management interventions can be used to achieve return to a pre-disturbance state. In contrast, helpful resilience indicates the capacity of unassisted return to a pre-disturbance state.

Wicked resilience: Wicked resilience was inspired by the distinct nature between 'wicked' and 'tame' problems, and thus Glaser *et al.* (2018) concluded it is difficult or not possible to objectively describe the term. Wicked resilience refers to interlocking 'wickedly' resilient vicious cycles predominantly driving the impoverishment, overexploitation, pollution, and degradation of social-ecological systems. As such, a multi-level, multi-actor governance approach is required to overcome chronic, undesirable, and wicked resilience from the local to the global level.

2.2.1 The value of bridging concepts in sustainability sciences

As a *bridging concept* (sensu Davoudi et al., 2012), resilience has been used across many disciplines and has facilitated interdisciplinary approaches to diverse challenges in the Anthropocene, particularly in social-ecological systems (Baggio et al., 2015). Several key benefits can be achieved when concepts travel across disciplines: 1) it prevents duplication of similar concepts under different names; 2) methods and approaches can be borrowed across disciplines leading to more powerful analytical approaches to explore system dynamics—e.g., modelling approaches in social-ecological sciences (Lade et al., 2017; Ngonghala et al., 2017); and 3) inter-disciplinary cross-talk allows a rich and malleable discussion of ideas enabling the development of more plausible solutions to complex environmental, social and economic problems (Brand & Jax, 2007; K. Brown, 2015). Whilst some level of conceptual vagueness and ambiguity can be helpful for interdisciplinary interaction (Brand & Jax, 2007), a distinction must be made between a concept's *intention* (its meaning, its ontology) and its *extension* (the phenomena to which it applies) to prevent its uncritical use (problematic concept "stretching" - Sartori, 1970). In this paper, we argue that the extension of resilience is stretched too far when it is used to account for both desirable and undesirable properties of SES without appropriate clarification.

A central challenge for research is how to coherently grasp the differences and interrelations among sustainability, resilience and transformation (Folke et al., 2010) through plausible and reconcilable approaches (Irwin et al., 2018). Despite growing recognition of and evidence for self-reinforcing mechanisms and *vicious cycles* in social and ecological systems, many studies tend to pay attention predominantly to 'building' or 'enhancing' resilience and thereby neglect 'breaking' undesirable resilience (Barnosky et al., 2012; Glaser et al., 2018; Oliver et al., 2018). Brown (2015, p. 36), for example, argues that despite resilience thinking carrying potential solutions for challenges of the contemporary age: *"... in many cases, resilience ideas are used to support and promote business as usual and not to challenge the status quo*". Resilience thinking and policy inevitably need to revaluate the existence of different academic and non-academic values, worldviews and framings of sustainability issues (Davoudi et al., 2012; Miller et al., 2014) to understand non-linear, complex features and uncertainty of change in SES (Folke, 2016). Identifying the uncritical use of resilience as a potential issue can be used as an opportunity to initiate transformative change (Chapin et al., 2010), in particular understanding and overcoming mechanisms of undesirable resilience.

In this paper, we explicitly distinguish *resilience* (increasingly used as a normatively desirable property) from *undesirable resilience* that hinders systems transformations towards sustainability. Through a citation analysis of the frequency and evenness in the use of various understandings and labels referring to undesirable resilience across disciplines, we assess the potential of these terms to serve as a bridging concept for sustainability science. We hypothesize that, in comparison to the single term *resilience*, different synonyms of undesirable resilience have been used in disciplinary silos – and are, therefore, less evenly referred to across disciplines, which limits their potential to serve as a bridging concept. This 'silo effect' can be particularly problematic in sustainability and SES research when: 1) different terms are used across disciplines to describe essentially equivalent or highly-related concepts; and 2) isolated disciplinary inquiries artificially deconstruct intertwined aspects of SES into a mere sum of the ecological or the social "parts" (Reyers et al., 2018). However, considering how the science system as it is today evolves, this 'silo effect' might also be a result of scientists being forced to enter and establish new fields, which sometimes are only separated from other fields through different key-terms with similar meanings (Seppelt et al., 2018). To investigate our hypothesis, we analysed the academic literature in two databases over the last five decades: Web of Science (WoS) and Scopus. Our aim was two-fold: 1) to conduct a citation analysis of the standardized number of publications (i.e., frequency) and of the spread of papers published using synonyms of undesirable resilience across different scientific disciplines; and 2) to identify terms with potential to contribute to a common understanding and usage as a bridging concept for the comprehension of transformational change in SES.

2.3 Methods

2.3.1 Literature analysis

We conducted a literature analysis of papers published using the term *resilience* and several synonyms of undesirable resilience in WoS and Scopus academic literature collections from 1970 to 2018. Synonyms of undesirable resilience were identified during an interdisciplinary expert workshop held in Leipzig, 2018 and included: *undesirable resilience*; *institutional inertia*; *path dependency*; *lock-in*; *social traps*; *social-ecological traps*; *unhelpful resilience*; *maladaptation*; *perverse resilience*; *wicked resilience*. This set of terms composes a non-exhaustive list based on the input of participants from a range of disciplines (Supplementary Table 2.1 – Appendix 2). The term *resilience* was used as a benchmark for comparison. To precisely assess the number of *resilience* papers published that did not include our targeted terms, the total search results for *resilience* were subtracted by the sum of papers that included terms for *perverse resilience, unhelpful resilience*, *undesirable resilience*, and *wicked resilience*. Searches for publications were performed between June and August of 2018, filtered by terms used in their title, abstract and/or keywords. Based on a pilot analysis, the timespan for the literature search was divided into two periods—1970–99 and 2000–18—because a considerable number of synonyms of undesirable resilience emerged after 2000 (Figure 2.1). With this division we wanted to check for temporal differences and avoid anachronic comparisons in the usage of different terms.

For each term and time period in our dataset, we used the same terminology and categorization of scientific fields employed by WoS and Scopus: the first uses ‘broad research categories’ and ‘research areas’; while the latter uses ‘areas’ and ‘subject areas’ (Supplementary Figure 2.1 – Appendix 2). To conduct our search through the WoS ‘advanced research’ tool, each term was specified in the ‘topic’ field (covering title, abstract and/or keywords fields within a record) and the respective scientific disciplines were identified by specific ‘research area’ (e.g., Sociology) – each classified within ‘broad research categories’ (e.g., Social Sciences). Search results were restricted to the document type ‘articles’, considering all languages, and to ‘research areas’ with more than 70,000 publications. To enable the selection of appropriate peer reviewed published papers in the scientific fields and time frames filtered, only ‘Science Citation Index Expanded (SCI-EXPANDED)’, ‘Social Sciences Citation Index (SSCI)’, and ‘Arts & Humanities Citation Index (A&HCI)’ were searched as citation indexes. In Scopus, the ‘advanced search’ tool was used to explore articles published across different scientific fields (defined as ‘subject areas’) that contained our selected terms of interest in the publication’s title, abstract and/or keywords. Due to incompatible assignment of similar scientific fields between the two search engines, the data gathered were not merged and thus were analysed independently for WoS and Scopus.

2.3.2 Our integrative approach

We briefly describe the concept of *undesirable resilience* as social-ecological dynamics that reinforce vulnerabilities and/or hinder transformation towards sustainable development. ‘Synonyms’ used in this study are interpreted as different terms (i.e., linguistic and rhetoric elements) referring to identical or similar intentions or meanings of a concept (i.e., its ontology), but not necessarily to the same phenomena to which it applies (concept extension). This means that our argument for a ‘bridging concept’ does not intend to overwrite the nuances, specific processes or dimensions of terms described in their own literatures and contexts under a definitive unifying term. We rather aim to identify a term that can facilitate a common understanding of undesirable resilience and serve as a conceptual entry point for interdisciplinary communication. We find that there is potential for such a common understanding, because - although values, traditions and designs are inherently different across scientific disciplines – some features of the terms referring to *undesirable resilience* overlap (e.g., between *perverse* and *undesirable resilience*; between *social trap, path dependency,* and *lock-in*).

2.3.3 Qualitative analysis – terms and academic disciplines

All terms analysed were discussed by the author team during the Leipzig workshop and their definitions were described based on key bibliography and how concepts currently are used in SES research primarily (Box 2.1). Relevant academic disciplines in WoS and Scopus were selected based on their similarities and relevance to the study of the terms identified. To balance the comparison of observations in our main analysis using all terms identified, the total number of disciplines selected was held equal for the two datasets (n=9). In WoS, three broad research categories were explored: Arts & Humanities (AH), which included the research areas History and Philosophy (n=2); Social Sciences (SS), including Business & Economics, Government & Law, Psychology, and Sociology (n=4); and Life Sciences & Biomedicine (LS), containing Agriculture, Behavioral Sciences, and Environmental Sciences & Ecology (n=3). In Scopus, four research categories were explored: Health Sciences (HS), including the subject area Medicine (n=1); Life Sciences (LS), which contained Agricultural and Biological Sciences (n=1);

Physical Sciences (PS), consisting of Earth and Planetary Sciences and Environmental Science (n=2); and Social Sciences (SS), comprised of subject areas: Arts and Humanities; Business, Management and Accounting; Economics, Econometrics and Finance; Psychology; and Social Sciences (n=5).

A secondary analysis of twenty research areas specifically for SS (n=10) and for LS (n=10) broad research categories was conducted separately to further investigate the use of terms *resilience, lock-in,* and *undesirable resilience* in WoS. Social Sciences included Area Studies, Business & Economics, Development Studies, Geography, Government & Law, International Relations, Psychology, Social Issues, Sociology, and Urban Studies. Life Sciences & Biomedicine contained Agriculture, Anthropology, Behavioral Sciences, Biodiversity & Conservation, Developmental Biology, Environmental Sciences & Ecology, Evolutionary Biology, Marine & Freshwater Biology, Zoology, and Public, Environmental & Occupational Health. A literature search for this secondary analysis was performed in February 2019, filtering publications by terms used in their title, abstract and/or keywords. Due to different categorization, distinct assignment of academic disciplines, and a more representative use of the term *undesirable resilience* in WoS from 2000–18, this secondary analysis was not conducted in Scopus.

2.3.4 Quantitative analysis – frequency of use

Despite covering a substantial amount of the academic literature, no database is complete and balanced (Chadegani et al., 2013). Both databases contain biases that favour the frequency of natural, biomedical and engineering sciences over arts & humanities and social sciences (Mongeon & Paul-Hus, 2016). To control for this potential limitation and increase reliability of our analysis – i.e., comparing the number of papers published using the terms searched across different research areas – the number of articles published was standardized by the total number of papers published in each research area, as described below:

- Standardised number of publications: reflects the number of papers published using target terms (n) per total number of papers published in the research area (N) multiplied by one million (standard factor), i.e., expressed by papers per million papers.

$$n / N * 10^6$$

<u>2.3.5 Quantitative analysis – evenness of use</u>

To test our hypothesis that synonyms for undesirable resilience are used within siloed, disconnected disciplinary approaches, we calculated the evenness in the use of terms in published papers across research areas (WoS) and subject areas (Scopus). For each term, the coefficient of variation (CV; described below) of standardized number of publications (papers per million papers) was measured across academic disciplines.

- Coefficient of variation (CV): expresses evenness of use by a simple calculation of standard deviation (σ) over the mean (μ). It reveals the degree of dispersion around the mean and thus is a useful measurement to compare variance even if the standardized number of publications show highly different means for each of the terms assessed. This method has been used in ecology to assess the degree to which species abundance is spread evenly across discrete habitat types (Julliard et al., 2006). In an analogous way, we use this metric to assess how the number of journal papers using a specific term are spread across different disciplines. We rank disciplines from the lowest to the highest CV value (i.e., from more- to less-even use of terms across disciplines - Julliard et al., 2006), indicating terms that are more to less commonly shared across disciplines.

Additionally, Shannon-Wiener's (D^{SW}), Simpson's (D^{S}), and Berger-Parker's (D^{PB}) ecological indices (Baumgärtner, 2006) were applied to analyse the equivalent richness, abundance, and equitability (evenness) for each target term used across research areas. In our study, terms searched correspond to ‘species’ and research areas represent ‘communities’. The standardized number of publications were then ranked from more to less even use of terms across disciplines (high to low values for D^{PB} and low to high for all other metrics). Equations used are described below.

- Richness (D^R): the simplest measure of biodiversity of an ecosystem Ω is the total number of different species found in that system (n). In our case, ‘species’ was equivalent to ‘terms’ and n represented how many times each term was found across the nine different research areas. This is often referred to as species richness:

$$D^R(\Omega) = n$$

- Shannon-Wiener Entropy: summarizes the entropy of a community. It expresses the average amount of ‘information’ in the community comparing rare species ‘information’ to common species and their information value (proportional to the logarithm of their proportional abundance in the community, p_i). In our study, terms are equivalent to species and research areas are the communities.

$$H = -\sum_{i=1}^{n} p_i \ln p_i$$

- Shannon-Wiener Equitability (D^{SW}): calculated by dividing the Shannon diversity index (entropy) by its maximum (H_{max}). Therefore, it varies between 0 and 1 (or 0 and 100%), with higher values indicating more community evenness.

$$D^{SW} = H / H_{max}$$

- Simpson’s Index (D^S): If two specimens are randomly selected from a sample, the probability that they will be two different species is given by this index. In theory, this metric ranges from 0 (perfectly uneven) to 1 (perfectly even). It expresses a true probability value.

$$D^S = 1 \,/ \sum_{i=1}^{n} p_i^2$$

- Berger-Parker Index (D^{PB}): equals the maximum p_i value in the dataset, i.e., the proportional abundance of the most abundant type. If the Berger-Parker index is high, this means that the community is dominated by the most common species – i.e., it is not even.

2.4 Results

Results presented here are primarily from our search in the WoS focussing on literature published between 2000 and 2018 due to more a representative use of synonyms of undesirable resilience in this database. Results for Scopus broadly support the WoS results (Supplementary Results to Chapter 2, Supplementary Table 2.2, and Supplementary Figure 2.2 – Appendix 2), though the former reports them in ‘areas’ and ‘subject areas’ whilst the latter uses ‘broad research categories’ and ‘research areas’ for assignment.

Research using the term *resilience* has increased steadily over recent years (Figure 2.1). In WoS, in the research areas explored in our literature analysis, it has increased from 830 total papers using the term in their title, abstract and/or keywords between 1970–99, to 17,505 papers between 2000–18 (Table 2.1). *Resilience*, which may be used to denote both normative desirable and undesirable proprieties, is much more commonly used than *undesirable resilience* and its synonyms that explicitly account for undesirability

(Supplementary Figure 2.3 – Appendix 2), exceeding their combined use (4,256 papers) by more than four times from 2000 to 2018. In this period, *lock-in*, *path dependency*, and *social trap* are the most frequently used synonyms with 1,697; 1,069; and 845 publications, respectively. From 1970–99, combined use of synonyms of undesirable resilience (490 papers) represented approximately half of the publications that mention *resilience*, whilst *undesirable resilience* had a single appearance in 1994. Other synonyms of undesirable resilience emerged later: *social-ecological trap* first appeared in 2004, *perverse* resilience in 2009, *wicked* resilience in 2011 and *unhelpful resilience* was used for the first time as late as 2012 (Figure 2.1).

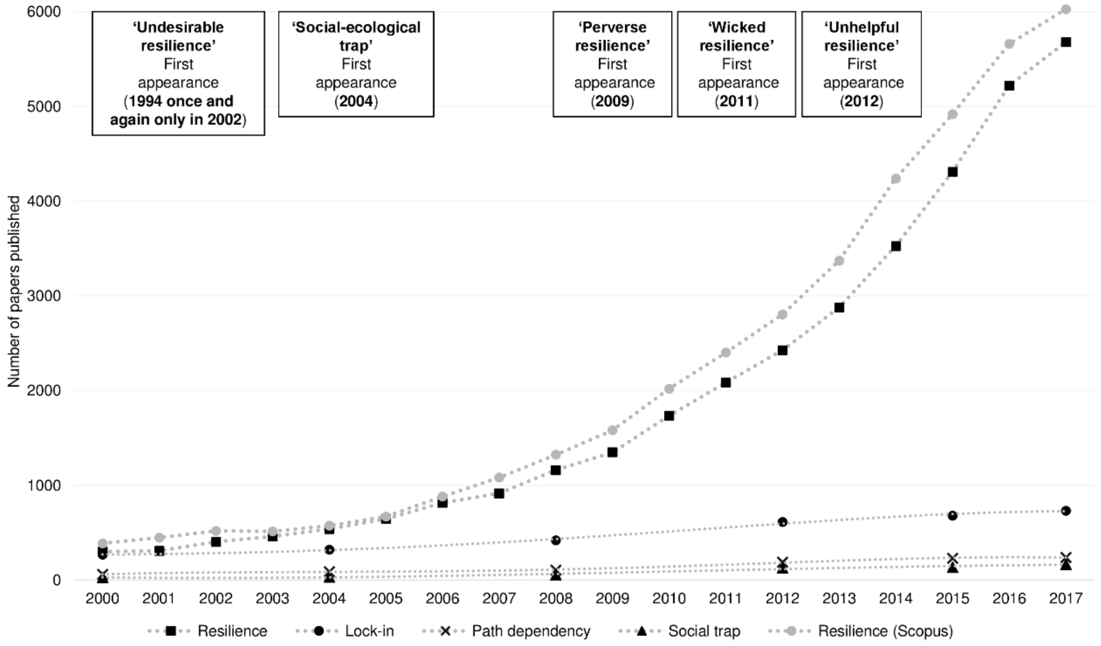


Figure 2.1 – Total number of papers published per year using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords in Web of Science since 2000 (and using the term resilience in Scopus). For terms emerging after 2000, first appearances are shown on the top of the figure. Total sum of papers published (and compound annual growth rate* between 2000–17) in Web of Science for the period were 41,479 (17.8%) for 'resilience'; 9,379 (5.7%) for 'lock-in'; 2,858 (8%) for 'path dependency'; and 1,687 (10.6%) for 'social trap'; whilst 'resilience' in Scopus was 44,106 (16.5%). Trend lines for other terms are not shown due to total sum of papers below 1,000 papers for the period, totalizing 262 for 'institutional inertia', 977 for 'maladaptation', 132 for 'undesirable resilience', 39 for 'social-ecological trap', 11 for 'unhelpful resilience', 48 for 'wicked resilience', and 9 'perverse resilience'. * The compound annual growth rate is measure of percentual increase per year and thus expresses the exponential growth of papers published using the term 'resilience' in comparison to other terms above, over the same time period.

Table 2.1 – Total number of papers published using the terms resilience and synonyms of *undesirable resilience* in their title, abstract, and/or keywords assigned across nine specific Web of Science research areas between 1970 and 2018.

	Total papers published		Terms									
			Resilience		Undesirable resilience		Path dependency		Lock-in		Social Trap	
Research Area	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18
History (AH)	128,911	129,744	14	175	0	0	2	34	4	39	3	24
Philosophy (AH)	81,223	103,325	7	91	0	0	0	15	3	28	4	16
Business & Economics (SS)	312,317	464,957	53	1,595	0	8	34	401	91	816	25	179
Government & Law (SS)	209,184	159,709	29	479	0	0	8	170	15	160	9	73
Psychology (SS)	429,978	518,496	301	4,850	1	5	17	70	17	90	33	70
Sociology (SS)	70,572	76,096	27	557	0	2	12	71	2	22	12	83
Agriculture (LS)	384,839	456,349	78	1,086	0	5	1	31	8	50	1	29
Behavioral Sciences (LS)	69,759	87,219	7	293	0	0	0	4	5	19	6	72
Environmental Sciences & Ecology (LS)	341,076	811,241	314	8,379	0	53	5	273	19	473	57	303

	Terms											
	Institutional inertia		Maladaptation		Social-ecological trap		Unhelpful resilience		Wicked resilience		Perverse Resilience	
Research Area	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18
History (AH)	0	7	2	3	0	0	0	0	0	1	0	1
Philosophy (AH)	0	2	2	4	0	0	0	0	0	1	0	0
Business & Economics (SS)	14	85	1	7	0	1	0	1	0	3	0	1
Government & Law (SS)	6	42	1	2	0	0	0	0	0	1	0	1
Psychology (SS)	0	3	42	89	0	0	0	1	0	1	0	0
Sociology (SS)	3	16	4	4	0	0	0	0	0	0	0	0
Agriculture (LS)	0	1	1	5	0	1	0	1	0	1	0	0
Behavioral Sciences (LS)	0	0	6	15	0	0	0	0	0	0	0	0
Environmental Sciences & Ecology (LS)	4	40	10	176	0	17	0	3	0	26	0	5

Synonyms of undesirable resilience are used substantially less frequently than *resilience* by standardized number of papers (i.e., controlling for differences in the total number of papers published in research areas). This is true across all nine specific WoS research areas from 2000–18 (Figure 2.2). Across three broad research categories (Arts & Humanities— AH; Social Sciences— SS; Life Sciences— LS) from 2000–18 in WoS, *resilience* is also the most frequent of our search terms. *Resilience* is at least four times more frequently used than all terms related to undesirable resilience in the AH literature; at least seven and 13 times more frequent in SS and LS respectively (Supplementary Table 2.3 – Appendix 2).

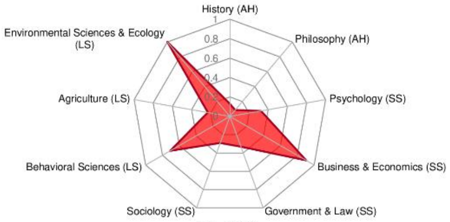
Among the three broad research categories, Arts & Humanities has the lowest use of synonyms of undesirable resilience (i.e., lowest percentage of publications using target terms) besides *perverse resilience*, *wicked resilience*, and *institutional inertia* (Figure 2.3). The terms *lock-in*, *path dependency*, and *institutional inertia* are more prevalent in Social Sciences, whilst *wicked resilience*, *social trap*, *unhelpful resilience*, *maladaptation*, *undesirable resilience*, and *social-ecological trap* are most predominantly used in Life Sciences & Biomedicine. Terms with the most even usage across all three broad research categories are *perverse resilience*, *lock-in* and *path dependency* (CV values of 0.43; 0.61; and 0.62 respectively), whilst *resilience* was ranked 4th (CV = 0.67), due to low relative frequency of use in Arts & Humanities.

Across the nine more specific WoS research areas, all synonyms of undesirable resilience are used more unevenly compared with *resilience* (lowest CV value of 0.76; reflecting the most even distribution across research areas; Figure 2.2). Synonyms of undesirable resilience that are most evenly used across research areas are: *social trap* (CV = 0.85), *path dependency* (CV = 0.95), and *lock-in* (CV = 1.03). Ecological indices Shannon-Wiener Equitability (D^{SW}) and Simpson's Index (D^{S}) identified an identical ranking for evenness of use across research areas: *resilience* is the term most evenly used (D^{SW} = 0.89; D^{S} = 0.83; higher values indicating more even use for these metrics), followed by *social trap* (D^{SW} = 0.87; D^{S} = 0.82), *path dependency* (D^{SW} = 0.82; D^{S} = 0.80), and *lock-in* (D^{SW} = 0.83; D^{S} = 0.79; Supplementary Table 2.4 – Appendix 2). Similar patterns are found in Scopus for the evenness of terms used across subject areas (Supplementary Figure 2.2 – Appendix 2).

Amongst synonyms of undesirable resilience, *lock-in* is the most widely used term in both absolute and standardised number of publications, with 1,697 publications using the term and 4,701 publications per million papers across all research areas. It is also used commonly across different academic disciplines: it is ranked 2nd and 3rd by evenness of use (i.e., with regard to the CV value) across broad research categories and specific research areas respectively (Figs. 2.2 & 2.3). Other synonyms that are also used across multiple research areas are *path dependency*, *social trap* and *perverse resilience,* but are all less frequently used than *lock-in* (n = 1,069; 849; and 8 absolute publications respectively). In a wider comparison of twenty research areas from two broad research categories (Social Sciences, SS and Life Sciences, LS), evenness of *lock-in* use (CV = 0.58 in SS and 0.85 in LS) is similar to the use of *resilience* (CV = 0.53 in SS and 0.77 in LS), while *undesirable resilience* is substantially less evenly used (CV = 1.38 in both SS and LS) across research areas (Supplementary Table 2.5; Supplementary Figure 2.4 – Appendix 2).

Resilience

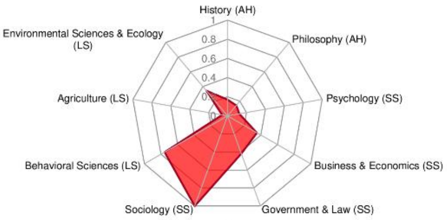
Scale: 1= 10,329 papers per million papers



CV= 0.76

Social Trap

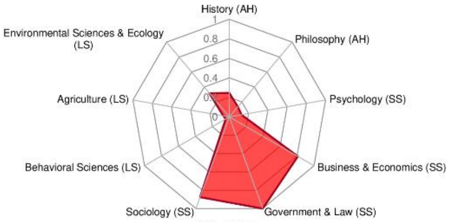
Scale: 1= 1,091 papers per million papers



CV= 0.85

Path dependency

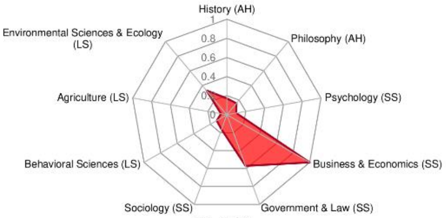
Scale: 1 = 1,064 papers per million papers



CV= 0.95

Lock-in

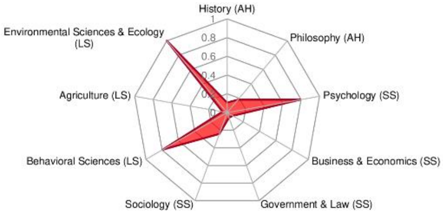
Scale: 1= 1,755 papers per million papers



CV= 1.03

Maladaptation

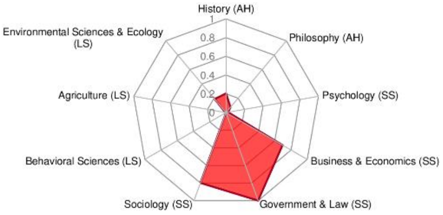
Scale: 1= 217 papers per million papers



CV= 1.04

Institutional inertia

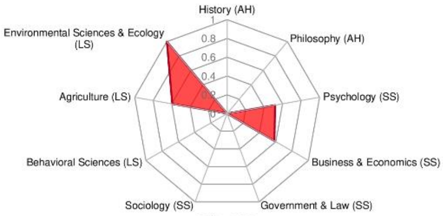
Scale: 1= 263 papers per million papers



CV= 1.17

Unhelpful resilience

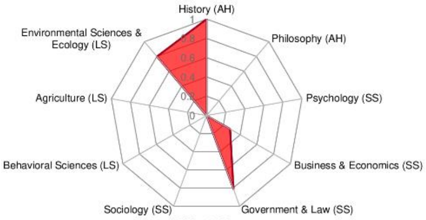
Scale: 1= 3.69 papers per million papers



CV= 1.27

Perverse Resilience

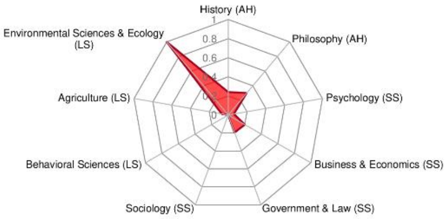
Scale: 0= 7.7 papers per million papers



CV= 1.32

Wicked resilience

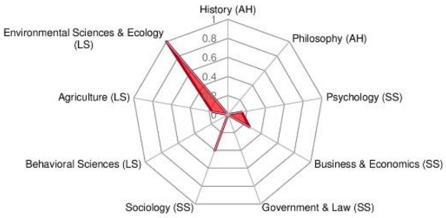
Scale: 1= 32.04 papers per million papers



CV= 1.34

Undesirable resilience

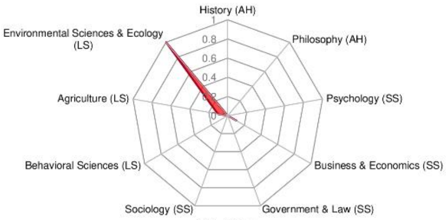
Scale: 1= 65.33 papers per million papers



CV= 1.48

Social-ecological trap

Scale: 1= 20.95 papers per million papers



CV= 2.44

Figure 2.2 (continued from previous page) **-** Standardised number of papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Web of Science research areas from 2000–18. Numbers of papers per million papers are plotted through a proportional scale ranging from 0 to 1, the latter representing the maximum value of standardised number of publications for each term across research areas. Radar graphs are ordered by CV (coefficient of variation) value, reflecting increasingly uneven use across the different research areas. Abbreviations: AH – Arts & Humanities; SS – Social Sciences; LS – Life Sciences & Biomedicine.

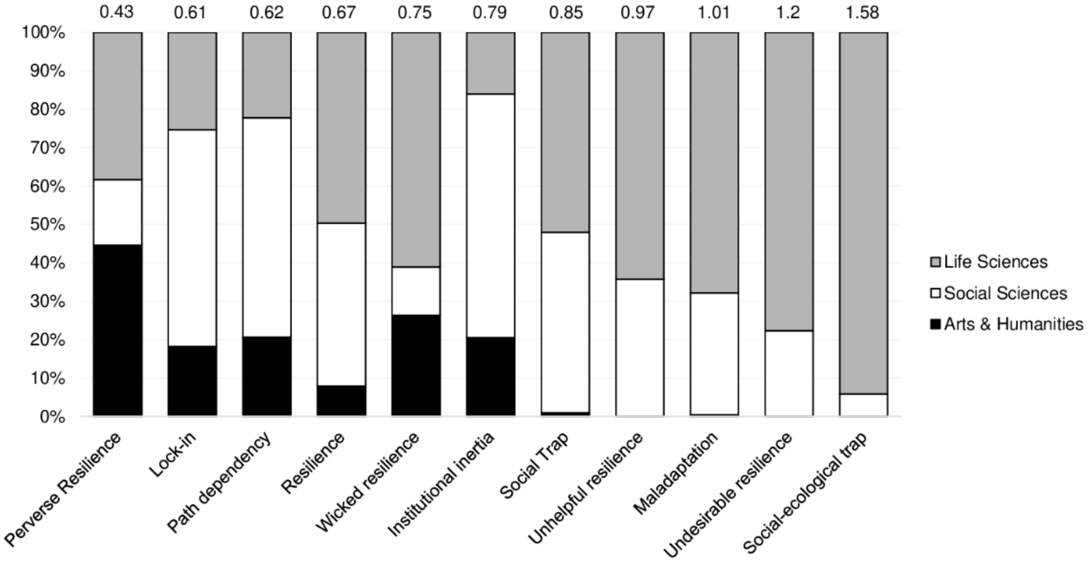


Figure 2.3 – Relative standardised number of papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across three broad Web of Science research categories from 2000–18. Bars are ordered by CV (coefficient of variation) value which is detailed at the top of the figure. Lower values reflect more even use across the three broad research categories.

2.5 Discussion

We found that papers using *undesirable resilience* and its synonyms are substantially less frequent than those using the term *resilience*. Simultaneously, publications using synonyms of undesirable resilience are usually restricted to specific scientific fields, shown by a lower spread of papers published across disciplines —supporting our hypothesis of a ‘silo effect’ that artificially and arbitrarily reduces intertwined parts of SES to explain them through isolated disciplinary inquires (Reyers et al., 2018). Amongst synonyms of *undesirable resilience, lock-in*, *path dependency*, and *social trap* are used more frequently and evenly across the disciplines explored. The combination of our quantitative and qualitative analysis suggests that *lock-in* appears to hold most potential as an informative interdisciplinary bridging concept.

Amongst the synonyms of *undesirable resilience* we investigated, the term *lock-in* ranked 1st for total and standardized number of publications and 2nd for evenness of use across broad research categories (3rd across specific research areas). Furthermore, based on a qualitative analysis of current definitions in the academic literature (Box 2.1) we argue that *lock-in* best reflects the positive (reinforcing) and negative (stabilising) feedback processes that prevent system transition from an undesirable equilibrium or trajectory. Other synonyms, like *path dependency* or *institutional inertia*, denote tendencies that conserve the status quo (by referring to historical deterministic properties or exclusively to the role of institutions, respectively), but do not necessarily capture the complexity of feedback dynamics inherent in resilient SES (Peters et al., 2005). The resilience of SES, be it desirable or undesirable, is influenced by a wide range of intertwined mechanisms and processes that lock-in the functioning and development of social-ecological interactions, which need to be examined holistically (e.g., cross-scale dynamics and systemic tipping points - Reyers et al., 2018). Therefore, *lock-in* broadens the scope of study beyond reductionist conclusions that describe states or trajectories of change restrictively. As the most frequently used of the *undesirable resilience* synonyms and as an integrative bridging concept, we find that *lock-in,* as term to designate *undesirable resilience,* has most potential to harness insights from life and social sciences to contribute to deeper understanding and purposeful management of sustainability transitions.

Further support for using *lock-in* as a bridging concept can be gained from its interrelation with the evolution of the concept '*tipping point'* - commonly used to refer to a rapid, potentially irreversible transition of a social or ecological system. Milkoreit *et al.* (2018) conducted an extensive review of similar terms that were used to describe this type of transition (e.g., *regime shifts, critical transitions*) and found that integration was particularly difficult due to at least 23 distinct disciplinary features for its definition—equivalent to the problem of concept stretching (cf. Sartori, 1970) for *resilience,* or to challenges of overlapping features shared across synonyms of *undesirable resilience*. The authors proposed a general definition for use of *tipping point* as a bridging concept: *"…the point or threshold at which small quantitative changes in the system trigger a non-linear change process that is driven by system-internal feedback mechanisms and inevitably leads to a qualitatively different state of the system, which is often irreversible*" (p.9 - Milkoreit et al., 2018). *Tipping point* is mostly used with reference to transitions away from desirable system states (i.e., a lack of *resilience* allows triggering of a *tipping point* into an undesirable state). However, a tipping process necessarily involves breaking resilience and can equally be surpassed to transition from an undesirable to a more desirable state or pathway. Hence, in relation to our focus on *undesirable resilience* here, overcoming *locked-in* situations (i.e., breaking *undesirable resilience*) can enable rapid system transformation towards more positive outcomes. In this sense, addressing underlying dynamics (*lock-in* mechanisms) that prevent *tipping points* towards achieving more desirable states is necessary to understand system transformations (TWI2050, 2018), but unveils conceptual challenges of its own.

2.5.1 *Lock-in* mechanisms: three challenges for an integrative concept for *undesirable resilience*

We identify three challenges for the use of *lock-in* as an integrative concept for *undesirable resilience*: 1) reconciling the mechanisms of desirable *resilience* from undesirable *lock-in*; 2) its inherent normativity; and 3) its extension across disciplinary boundaries. A first challenge for the interdisciplinary use of *lock-in* is the reconciliation between aspects of desirable *resilience* and undesirable *lock-ins* across a hierarchy of time scales, spatial scales and different actors. Although we argue that the term *lock-in* is a useful point of interdisciplinary convergence, we need to carefully consider its application as an extendable concept. To distinguish desirable from undesirable *resilience* requires reflexivity to deconstruct the various mechanisms that sustain or *lock*-in undesirable SES states or trajectories. For example, Oliver *et al.* (2018) identified over 20 different mechanisms that prevent the transformation of food systems towards configurations that are less environmentally and socially damaging (they grouped *lock-in* mechanisms into four categories: knowledge based, economic/regulatory, sociocultural and biophysical). Similar approaches could be taken to deconstruct *lock-ins* that constrain the reversal of anthropogenic pressures in different earth systems (Seppelt et al., 2014; Steffen, Richardson, et al., 2015), as well as identifying interdependent constraints in achieving goals of well-being and development (Raworth, 2017).

We considered two important characteristics of the first challenge for an integrative definition of lock-in that can address *undesirable resilience* in different contexts: reversibility and plausibility. In some contexts, even though *lock-ins* are technically reversible (i.e., “hysteresis” can be overcome - Milkoreit et al., 2018), they may still be implausible to overcome due to dynamic interactions pushing the system towards undesirable outcomes (e.g., co-existence of *social-ecological traps* and *institutional* *inertia* that synergistically reinforces vulnerabilities). On the other hand, it might be plausible to prevent reaching an undesirable irreversible tipping point if reasonable conditions support an agreement among stakeholders to implement innovative interventions towards more desirable or just forms of sustainability. In other words, it is essential to understand the plausibility to address *lock-in* mechanisms to prevent reaching irreversible tipping points or strong hysteresis. For a more comprehensive understanding of the dynamic mechanisms behind undesirable states or trajectories leading to undesirable tipping points, we argue that three potential intersections between the reversibility and plausibility to overcome problems can be summarized as: ‘hard’ *lock-in* mechanisms (i.e., a combination of strong social-ecological drivers and strong hysteresis or irreversible tipping points); ‘soft’ *lock-in* mechanisms (i.e., weaker social-ecological drivers and weak hysteresis); and tame problems (apparent absence of *lock-in* mechanisms: reversible and plausibly resolvable problems; Supplementary Figure 2.5 – Appendix 2).

The second challenge for an integrative concept concerns the inherent normativity, such as in the term *lock-in*, that addresses *undesirable resilience*. Defining what is (un)desirable *resilience* inevitably implies normative and moral judgements and thus raises questions on equity, agency, distribution of power and politics (Boonstra, 2016; Davoudi et al., 2012). It means that if the undesirability of *resilience* is not explicitly debated, taking into account values, interests and power (shaping both conduct and context - Boonstra, 2016), the concept runs the risk of inappropriately informing management and policy. For example, it might result in “*societal adaptation and resilience to sustained unsustainability*” (p. 10 - Blühdorn, 2016) or it might be used to justify initiatives favouring incremental adaptation only (Reyers et al., 2018). Once the normative assumptions around resilience ‘of what’, ‘to what’, ‘for whom’, and ‘at what time scale' are made explicit, it enables a more reasonable distinction of how and why change towards sustainability can be implemented (Helfgott, 2018; Weise et al., 2020). Scholars working on the interrelated paradigm of sustainability argued that the politics of *unsustainability* (Blühdorn, 2016) turned "*sustaining the unsustainable into an imperative*" (p. 9) rather than aiming to deliver structural changes to prevent undesirable social conflicts and ecological collapse. Clearly it is important to avoid the potential of conceptual stretching in the uncritical use of *lock-in*.

The third and final challenge to consider relates to the extension of the term *lock-in* to address the concept of *undesirable resilience* across disciplinary boundaries. A coherent interdisciplinary approach to *lock-in* mechanisms, using terminology consistently across disciplines requires academic humility and reflexivity to recognize that different cultural values and perspectives that underpin scientific disciplines (Rockström et al., 2018) and to acknowledge distinct working traditions. Notwithstanding the value of this diversity, interdisciplinary integration is highly worthwhile in sustainability science, where concepts and methods need to be integrated to enable communication and synergies in order to progress sustainability thinking within as well as beyond academia (i.e., transdisciplinary research - Lang et al., 2012).

Overcoming these challenges is warranted not only to establish *lock-in* to differentiate undesirable from desirable *resilience*, but also to enable a richer analysis of the mechanisms leading to undesirable states or trajectories. The explicit attention to *undesirable resilience* and mechanisms of *lock-in* can help to better understand social-ecological dynamics and, consequently, contribute to designing appropriate interventions. For example, in a poverty trap study using multidimensional models, Lade e*t al.* (2017) concluded that it is impossible to understand persistent poverty without explicitly accounting for multiple positive (reinforcing) and negative (stabilising) feedback interactions which, in respect to our study, might lead to persistent undesirable consequences in SES (i.e., *locked-in* systems). Transcending one-dimensional perspectives requires new theoretical advances to explore the interplay between mechanisms that underpin traps, potential alleviation strategies and wider social-ecological factors. Similarly, Ngonghala *et al*. (2017) found that negative feedbacks between ecological, economic and epidemiological parameters are of primary importance for developing integrated interventions to tackle persistent poverty.

Lock-in mechanisms and complex feedbacks are also important to explore the potential interaction between simultaneous trajectories and goals. In processes of agricultural transition and urbanization, mutual-reinforcement of technological change, population growth and patterns of urbanization can potentially lead to social-ecological traps and ecosystem over-exploitation (Cumming et al., 2014). Finally, acknowledging *lock-in* mechanisms can help to interpret obstacles and guide planning in holistic and multidimensional models of interactions (synergies and trade-offs) amongst, for instance, the United Nations Sustainable Development Goals (Pradhan et al., 2017). Hence, identifying and quantifying the self-reinforcing and often non-linear features that *lock-in* SES to undesirable states or trajectories is a crucial focus for progressing sustainability science and transitions.

Bearing in mind these three challenges, we identify an opportunity for the term *lock-in* to contribute as an integrative concept for understanding *undesirable resilience* in sustainability science. As an extendable concept, its coherent use must carefully consider underlying values and conceptual complexity from different scientific perspectives, and appropriately incorporate plurality of understanding among disciplines. Common understanding and usage of *lock-in*, in this sense, have potential to simultaneously: 1) describe the mechanisms that reinforce vulnerabilities and/or hinder transformation towards sustainability across disciplines; 2) raise awareness of highly relevant aspects of *undesirable resilience* that are often overlooked; 3) facilitate conceptual progress while maintaining rich and diverse discussions; and 4) improve the consistency of discourse and research as a complementary concept to *resilience* in sustainability science.

2.5.2 Reflections on the literature analysis

To our knowledge, this is the first study to quantitatively assess the frequency and evenness of use of synonyms of *undesirable resilience*, and to qualitatively identify and compare them across different disciplines in the academic literature. To this purpose, we explored two academic literature collections: WoS and Scopus. They both cover the majority of published scientific material, but some limitations must be considered. A key constraint is the incompatibility between the two datasets that stems from the use of different terminology and criteria for the assignment of papers across scientific disciplines. Differences in how, for example, 'research areas' (WoS) and 'subject areas' (Scopus) categorize publications complicate comparison. Although WoS and Scopus might use similar names for research and subject areas, these include different sub-categories and are also aggregated differently into 'broad research categories' (WoS) or 'areas' (Scopus). This inconsistency in assignment and categorization becomes very clear for multidisciplinary research: 'Multidisciplinary Sciences' is categorized as a specific subject category in WoS, whilst 'Multidisciplinary' is assigned under Health Sciences in Scopus. Thus, we could not directly compare results between WoS and Scopus, but only through standardised numbers of papers and different indices of evenness of use across disciplines within each academic repository separately. In summary, by considering the two databases our search has been considerably exhaustive.

2.6 Conclusion

As a bridging concept, *resilience* has been useful in developing interdisciplinary collaboration and synergy for sustainability science. Yet, with the growing use of the term across disciplines, important distinctions are lost, which limit its ability to inform sustainability transformations that often require overcoming negative feedback mechanisms that trap systems into undesirable states or trajectories. In this paper, we suggest drawing a distinction between *resilience* and its overlooked flipside *undesirable resilience*. Here we found that research on synonyms related to *undesirable resilience* is not only substantially less frequent in comparison to *resilience*, but also tends to artificially deconstruct intertwined parts of SES to explain them through specific scientific fields with their own distinct terms. Of these synonyms, the term *lock-in* is the most frequently and commonly used across several scientific disciplines. To address the lack of a common understanding of *undesirable resilience,* we argue that *lock-in* offers opportunity as a bridging concept that allows quantitative and qualitative analysis of constraint mechanisms—explicitly and coherently addressing characteristics of reversibility and plausibility. Common understanding and usage of *lock-in* can integrate insights and methodologies across disciplines contributing to sustainability science, can improve the consistency of *resilience* thinking as a complementary concept, and thereby enable a more comprehensive exploration of social-ecological dynamics towards more sustainable futures. Finally, work remains to be done to reconcile normative assumptions and moral implications of (un)desirable aspects of *resilience* across a hierarchy of time scales, spatial scales and different actors.

2.7 Declarations

2.7.1 Conflict of interest

None.

2.7.2 Publishing ethics

This research and article comply with *Global Sustainability*'s publishing ethics guidelines.

2.7.3 Data availability statement

The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Material. All of the data were extracted from the Web of Science (https://clarivate.com/products/web-of-science) and Scopus (https://www.scopus.com) academic collections, and the exact search string is described above.

2.7.4 Supplementary material link

The supplementary material for this article can be found at https://doi.org/10.1017/sus.2020.15

CHAPTER 3

BREAKING LOCK-INS FOR SOCIAL-ECOLOGICAL TRANSFORMATIONS

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Emily Boyd, André Dornelles, Izabela Delabre, and Genesis Tambang Yengoh contributed to the ideas and design of the paper. Emily Boyd, André Dornelles, Izabela Delabre, and Genesis Tambang Yengoh wrote the article, reviewed and provided critical comments to the paper. All authors contributed to the final review and editing of the paper.

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3.1 ABSTRACT

Sustainability and transformation sciences inevitably require identifying challenge-oriented patterns in social-ecological systems and making normative judgments about desirable and undesirable trajectories and/or states. Transformation research aims to foster transitions and innovations, but it does not pay sufficient attention to the mechanisms needed for doing so. Resilience research provides insight into mechanisms of change, adaptation or stability, but it tends to mainly frame resilience as a desirable property and overlooks persistent dynamics that lead to social and ecological degradation, vulnerability, or barriers that hinder sustainability transformations. Here, we aim to operationalize a comprehensive understanding between the undesirable properties of resilience (lock-ins) and their impacts on transformations towards sustainability, through a lens of O'Brien and Sygna's three spheres of transformation: personal, political, and practical. The study draws on four social-ecological themes and associated case studies to define and analyse case-specific lock-in mechanisms and therefore enrich our understanding of how states and trajectories may be disrupted and shifted onto more sustainable pathways. These case studies relate to important social-ecological challenges: pollinator decline, negative emissions technologies, plastic pollution, and increasing meat demand for human consumption. Our analysis reveals 'enabling conditions' – sharing common elements with multiple lock-ins (inter-locked mechanisms) – that can bring synergistic benefits for sustainability transformation across different social-ecological challenges. Understanding these foundations from which means of transformation occur can provide meaningful insights to successfully crack persistent lock-in mechanisms.

3.2 Introduction

Over the last two decades, “resilience” has developed into a central concept in many disciplines related to sustainability research and practice. It also is referred to by policy makers, administrations, governments, and international organizations and companies (Callaghan & Colton, 2008; Ogden et al., 2013). The United Nations (UN) Sustainable Development Goals (SDGs) explicitly emphasize the objective of taking *“transformative steps…to shift the world onto a sustainable and resilient path”* (UN, 2015). Although countless specific definitions of resilience exist (Baggio et al., 2015; Brand & Jax, 2007; Donohue et al., 2016; Zhou et al., 2010), it generally refers to the preventive and reactive capacities to resist or absorb a disturbance, to recover from stress or shocks, to reorganize through adaptation, and to reorient through transformation in order to maintain essential functions (Folke et al., 2010). The popularity of this concept reflects the growing concerns for the sustained functioning of ecological, social, and social-ecological systems in the face of unprecedented rates and magnitudes of changes in the environment (Folke, 2016). ‘Low’ or ‘weak’ resilience of social-ecological systems impairs its capacity to transform or bounce back after a shock (Walker et al., 2006). Once the resilience of a social-ecological system has been impacted or stressed and a threshold has been surpassed at a certain “tipping point,” a sudden regime shift may occur to a new, degraded regime where desired ecosystem functions and services are degraded or lost. In ecology, key examples of regime shifts include: eutrophication of lakes, collapse of a key species such as the Atlantic cod, or bush encroachment in savanna rangelands (Stockholm Resilience Centre, 2019).

While most sustainability literature considers resilience as a desirable property that management and policies should protect, restore, or strengthen, resilience can also have undesirable properties if it prevents us from transforming systems away from unsustainable states or trajectories. Undesirable “lock-ins” refer to situations of resistance to change, notwithstanding awareness that a practice, technique, input, or process may have undesirable long-term implications, or lead to social-ecological traps (Nair & Howlett, 2016). Lock-ins can be understood as the process by which systems acquire momentum through the alignment of actors, materialities, and practices with vested interests in system preservation and growth, and lock-ins are deeply dependent on societal acceptance (Essebo, 2013). Social-ecological traps are processes in which social and ecological vulnerabilities mutually reinforce each other, hence maintaining or pushing social-ecological systems towards an undesirable state or trajectory (Boonstra & de Boer, 2014; Nair & Howlett, 2016). Such traps tend to be hard to escape if proposed solutions are limited to making piecemeal or incremental changes. Anthropogenic activities are currently socially and ecologically unsustainable in many ways, and thus transformations of undesirable states and trajectories are required. Desirable resilience focuses on adaptation for conserving a desirable state (i.e., outcome), implying self-organizing responses to ongoing massive changes in environmental and societal drivers of harm (Folke et al., 2010; Walker et al., 2004). Moreover, whilst the discussion of desirable resilience often is caught up in terminological sham fights (“what ‘is’ resilience?”), addressing lock-ins to undesirable states more directly prompts an action-oriented question on: what can we do about it? Given this normative agenda, we thus see lock-in as an important complementary concept to desirable resilience, but currently underexamined.

This study starts from the question: how can we understand lock-ins in order to break them for social ecological transformations? We aim to identify and understand specific lock-ins in the four cases and, second, to operationalize a comprehensive understanding between the undesirable properties of resilience and their impact on mechanisms for transformations towards sustainability. Understanding lock-in mechanisms is of fundamental value not only for identifying key leverage points for sustainability transformation (Abson et al., 2017) but also to better understand the potential of social-ecological system (SES) transformations. This allows us to examine and evaluate existing structures that are or will become resilient, thereby providing the opportunity to bridge between ecological and social understandings of resilience and systems. Examples of undesired states, or regimes, in political and social systems, include: poverty, racism, or authoritarian dictatorships. Examples of undesired trajectories are increased income differences between the rich and the poor (Piketty, 2015), or food systems fostering unsustainable monocultures (Oliver et al., 2018) and subsequent loss of biodiversity (Storkey et al., 2012). Instead of focusing on desirable resilience (release or freedom) only, we tackle this urgent research gap by investigating the connection between (un)desirable resilience (lock-ins) and transformation (social-ecological change).

3.3 Concepts & analytical lens

This article was designed as a synthesis, integrating elements that historically have been considered separately, in order to suggest new opportunities for theory, policy, and/or practice. Our analysis aims to identify and analyse lock-in mechanisms in relation to four case studies, in order to understand how states and/or trajectories may be disrupted and shifted onto more sustainable pathways; thus enabling transformations towards sustainability. We examine case studies that are symptomatic of, and/or sustain, states and/or trajectories of undesirable properties of resilience in social-ecological systems. These include: (1) pollinators decline in relation to ecosystem loss and pesticide use, (2) overreliance on negative emission technologies to mitigate climate change; and (3) plastics pollution, and (4) increasing demand of animal foods for human consumption.

These four cases were selected by the authors during an interdisciplinary workshop held in Lund University in 2019. The criteria and reasons behind the selection of the four case studies are due to the importance and urgency of significant social and ecological risks caused by current practices and trends: insect populations globally are at risk of collapse (Sánchez-Bayo & Wyckhuys, 2019); carbon dioxide emissions are increasing and temperatures are heading towards a 2°C average increase above pre-industrial levels (IPCC, 2018); there has been a substantial increase in plastic production and poor waste management causing extensive plastic pollution of land and oceans (Borrelle et al., 2017; Haward, 2018); and livestock is responsible for high environmental burden despite delivering a relatively small nutritional caloric contribution (Poore & Nemecek, 2018; Springmann, Clark, et al., 2018). The cases are analysed to identify lock-in mechanisms, as well as transformation trajectories across the personal, political, and practical spheres. Interrogating these four cases of social-ecological challenges allows for an examination of case-specific lock-in mechanisms, which may also reveal (inter)lock-ins that impact the wider themes, and exposes the enabling conditions, to provide a means for transformation across these themes.

3.3.1 Resilience and transformations

There is common understanding that social-ecological resilience can lead to sustainable transformations (Folke et al., 2002, 2010), with an important role of power to understand integrative approaches in patterns of transformation, innovation and social-ecological-technological systems interactions, and the function of agency in sustainability transformations (P. Olsson et al., 2014). Models and theories of social-ecological systems identify how resilience contributes to maintain positive functional properties of SES (e.g., social cohesion, ecosystem services) in the face of external shocks (Biggs et al., 2012; Oliver et al., 2015; Ostrom, 2009; Scheffer, 2009). Such resilience research has a growing empirical basis, in both social and natural sciences. However, SES transformations toward sustainability require transformative change, which can be hindered by certain factors causing the system to remain ‘locked-into’ an unsustainable state or trajectory (Figure 3.1). Rapid, non-linear, and unpredictable changes occur in many social-ecological systems (Stirling, 2010), which increases the difficulty to define and understand system boundaries, cross-scale dynamics and systemic tipping points (Reyers et al., 2018). Additionally, the trends of social-ecological systems trajectories are often hard to stop or revert, meaning that the limits to human intervention represent an aspect of resilience itself. In this sense, underlying mechanisms that lock in the functioning and development of intertwined social and ecological interactions are important determinants of (un)desirable resilience of social-ecological systems.

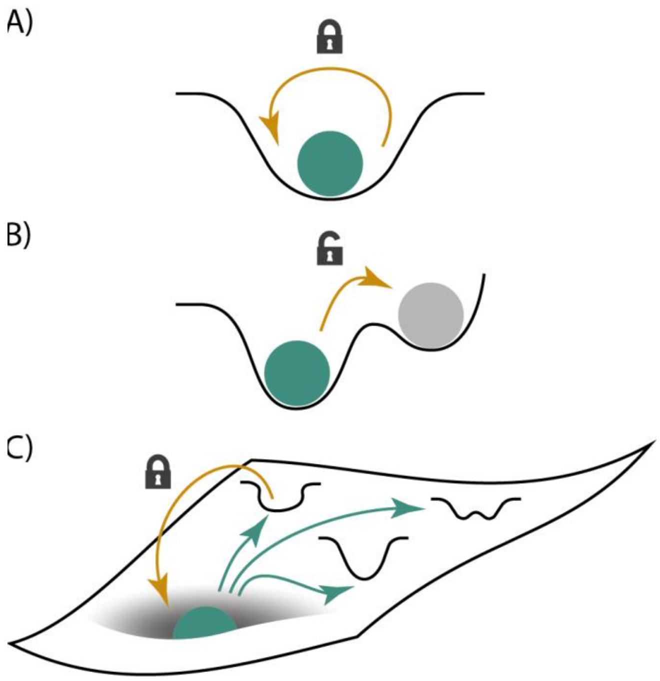

Figure 3.1 – Anatomy of lock-in mechanisms in transformation (based on the 3D stability landscape from Walker et al., 2004). There are different states of lock-ins. A) Sometimes the alternative to overcome undesirable states is to move back to a previous state (e.g., biodiversity loss) B) whilst other times the alternative is to move forward to an alternative (e.g., removing plastics from ecosystems). C) A 3D landscape representing different alternatives to overcome lock-ins (i.e., moving out from the hole). There is no silver-bullet or single alternative, but different pathways / trajectories for addressing lock-ins and unlocking transformations.

3.3.2 Transformations: personal, political, and practical spheres.

Over the past decade, research on transformations has become a growing focus within sustainability science with the entry of new disciplines over time and new ideas fertilizing sustainability discourse (Leach et al., 2010, 2012; Meadowcroft, 2009; O'Brien, 2012; P. Olsson et al., 2014; Pelling, 2011; Smith & Stirling, 2010; Stirling, 2011). In general, there are four more established framings of transformations to sustainability, including: transitions approaches (derived from social-technological studies, complex systems thinking, and institutional economics), social-ecological transformations (exploring the interdependence between transformations and resilience thinking), sustainability pathways (emerged from the intersection between development studies, resilience, and planetary boundaries), and transformative adaptation (with roots in human geography and political ecology - Blythe et al., 2018; Feola, 2015). In this study, we explore elements of transformations from all of these perspectives in a holistic manner, aiming to investigate communalities and differences in the activity of mechanisms of change, target outcomes in relation to social-ecological challenges, and the objects of transformation across four case studies (Few et al., 2017).

O'Brien (2017) suggests that societal transformations challenge traditional ways of thinking about doing things, and planning for the future. Beck and Mahony (2017) characterize transformations as change that contains agency and that represents differentiated impacts on people and groups in society at different scales. Still ideas of societal transformations under environmental change often focus on how societies can shift away from current trajectories of unsustainability given the limitations of governance, missing institutions and economic structures, social norms, and identities (Pelling, 2011). Models of transformation, however, often fail to systematically account for how people understand, feel, and perceive the significance of fundamental sustainability transformation challenges. Moreover, the lack of desire to transform existing structures is reflected in the so called ‘action gap’ between the subjective personal, political, and practical (O´Brien & Sygna, 2013).

To explore the ‘lock-in’ mechanisms that keep a system locked into an undesirable state and/or trajectory, we critically examine three focal examples: (1) biodiversity and ecosystem loss, (2) climate change and (3) overconsumption of resources. To identify specific lock-ins and opportunities for change, we examine the three spheres of transformation identified by O’Brien and Sygna (2013): the practical, political, and personal spheres. The three spheres need to be viewed interdependently and in order to appropriately acknowledge the breadth and depth of transformations and the multiple levers for change towards sustainability (Sharma, 2007).

Following O’Brien and Sygna’s (2013) framework, the practical sphere represents the core sphere, and includes behaviours and technologies related to conditions of (un)sustainability. The lock-in mechanisms within this sphere therefore include certain types of persistent behaviour, social norms, current technologies. Thus, relating to transformations, the practical sphere involves behavioural changes, social and technological innovations, and institutional and managerial reforms in addressing those lock-in mechanisms. Attention to this sphere is currently the main focus in relation to climate policy and technical responses to climate change (O’Brien, 2018). The political sphere includes the social and ecological systems and structures that create the conditions for both lock-ins and transformations in the practical sphere, thus, enabling or disenabling conditions necessary in the process of reaching targets or goals (O´Brien & Sygna, 2013), such as the SDGs. The personal sphere includes individual and collective beliefs, values and worldviews that shape the political sphere by shaping how systems and structures are understood, and what solutions in the practical sphere are possible (O´Brien & Sygna, 2013).

Interventions have the potential to be transformational (O’Brien et al., 2014) yet they are often based on simple models and limited understanding of what constitutes resilience (Lade et al., 2017). There is an emerging critical perspective on the limits to resilience (L. Olsson et al., 2015). Furthermore, current understanding of the function and feedback between negative resilience and the positive interventions or levers that unlock transformative capacity are still poorly understood. One example is the relatively unknown relationship between the use of fertilizers, the emergence of pests under climate change affecting important commodity food crops (e.g., maize, cocoa, coffee, or bananas), effects on losses of ecosystems, and factors compounding chronic poverty, poor health, and gender inequality (FAO, 2017).

3.3.3 Transformation spheres and lock-ins

Lock-in mechanisms can be perceived in any of the three spheres of transformation. Resilience in continuing preconceptions after exposure to new information on science and policy of climate change has been documented in the personal dimension (Sunstein et al., 2017). The tendency of some institutions to resist change and stabilize detrimental policies often leads to inertia of the practical sphere (Rosenschöld et al., 2014). Persistent justifications for excluding women from education and society are still deeply engrained in some cultures and contexts, related to the political sphere (Moaddel, 1998). Since transformations in any of these spheres may result in changes in others (Sharma, 2007), it is logical to expect that spheres locked into unsustainable states and/or trajectories can have multiple detrimental effects. This means that the persistent existence of vulnerabilities can further reinforce other vulnerabilities. For example, excessive inequality can lead to political polarization, erode social cohesion and finally lower economic growth (IMF, 2017). This also means that the longer it takes to transform unsustainable states and/or trajectories, the costlier it is to do so. If explicit cooperation to reduce greenhouse gas (GHG) emissions had started in 2000, for instance, only 4% reduction per year would be required to overcome growing global energy demands in comparison to more challenging 18% at present (Le Quéré et al., 2018). A deeper understanding of lock-ins and potential interventions in relation to personal, political, and practical spheres can thus help to reveal enabling conditions for unlocking synergistic barriers to sustainable and equitable transformations.

3.3.4 The role of collective action

The political sphere, described by O’Brien and Sygna (2013), represents the systems and structures that define the constraints and possibilities under which practical transformations occur. It is in this sphere that enabling conditions that allow for collective action can be mobilized and become a lever for transformative change. It has been argued that collective action for sustainability is required to attain the SDGs, by creating inclusive decision spaces for stakeholder interaction across multiple sectors, levels, and scales (Bowen et al., 2017; Stafford-Smith et al., 2017). Collective action, at multiple levels and across scales, brings together diverse actors with divergent and sometimes conflicting interests working towards a shared vision; and conflicting interests can pose significant challenges. From the negotiations and decisions conducted through collective action in complex political processes for sustainability, innovative practices, alliances, and ideas can flourish to tackle either new or old problems (Sandler, 2015). Nonetheless, it is important to bear in mind that collective action should not be understood as a recipe applicable in any given context: group size, group composition, or institutional design are factors that can influence adverse or inefficient outcomes (Sandler, 2015). Furthermore, in a context where enabling conditions are lacking, certain forms of collective action may emerge that are not sensitive to diverse politics and knowledges, or plural pathways. Such forms of collective action can risk the emergence of new lock-ins and have unintended consequences if pursued to the neglect of alternative, potentially more sustainable pathways (Figure 3.2).

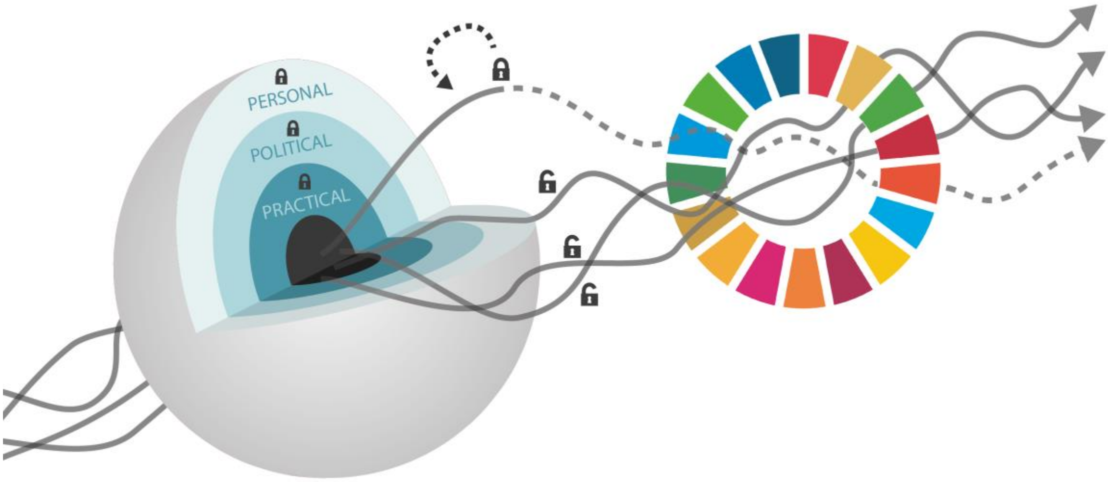

Figure 3.2 – Analytical framework: unlocking trajectories of transformations towards sustainability through enabling conditions for collective action. Left circle: P + P + P (personal, political, and practical spheres of transformation - O´Brien & Sygna, 2013); Right circle: the Sustainable Development Goals (SDGs). Grey arrows between the two circles: pathways towards the SDGs and how enabling conditions can break lock-ins and transform social-ecological systems (solid line, open lock) or, alternatively, how persistent lock-ins prevent transformations towards sustainability (dashed line, closed lock).

3.4 Case studies

3.4.1 Biodiversity and ecosystem loss focused on pollinator decline

3.4.1.a Case: pollinator decline

Pollination contributes significantly to global crop yield and food security (Aizen et al., 2009; Hung et al., 2018; Vanbergen, 2013) with up to three-quarters of the world's crop species depending on pollinators, for instance wild and domesticated bees, other insects, birds and even some mammals species (Aziz et al., 2017; Garibaldi et al., 2013; Sihag, 2018). It is estimated that between 75% and 95% of all flowering plants on the earth require pollination services (Ollerton et al., 2011; Potts et al., 2010). However, pollinators and pollination services are under threat, and the 'pollination crisis' has risen in public consciousness (Suryanarayanan, 2014). This 'crisis' refers to the mass decline and extinction of pollinators and associated impacts on crop production and ecosystem services, a phenomenon observed by scientists and agriculturalists since the mid-1990s (Goulson et al., 2015; D. Roubik, 2018).

3.4.1.b Lock-in mechanisms

A key lock-in mechanism leading to the pollinator crisis has been the push for global agricultural intensification and its accompanying practices. This includes the proliferation of pest control chemicals, including biocides or pesticides (Sihag, 2018; Vanbergen, 2013), plant growth regulators, fruit thinners, and fertilizers (Brittain et al., 2010; Potts et al., 2010; Winfree et al., 2009).

In general, economic returns from short-term increases in agricultural output (through pesticide use) align with private interests. Pest control practices are considered legitimate if compliant with health and safety regulations designed to protect people and the environment. The persistent use of non-specific pesticides is detrimental to pollinator services (Potts et al., 2010), but there still remains uncertainty around the long-term effects of such chemicals (Smith et al., 2013; van der Sluijs et al., 2013; Woodcock et al., 2016). In the political sphere, the limited role played by the precautionary principle in defining safe levels of pesticide use contributes to a lock-in. In the practical sphere, enforcement to prevent the use of harmful and/or illegal pesticides has been found to be very weak (e.g., persistent use of highly toxic *Paraquat*). For example, nine of 21 pesticides listed as “highly hazardous” on the PAN (Pesticides Action Network) list are still permitted in Brazil, despite being banned across the EU due to their harmful effects (Public Eye, 2019). Therefore, lock-in mechanisms in spheres of transformation manifest in persistent unrestrictive laws that fail to regulate pesticides, the lack of law enforcement, and the power of industry lobbying power; thus, reinforcing vulnerabilities and/or hindering transformation.

Changes in land use and landscape structure, habitat fragmentation and degradation have also contributed to pollinator population loss (Potts et al., 2010). In addition, the limited knowledge about pollinators, and targeted hunting by local farmers also exacerbate the loss of pollination services (Anderson et al., 2011; Aziz et al., 2017). Moreover, domestic bee colonies are increasingly vulnerable to disease (Smith et al., 2013; Vanbergen, 2013). Furthermore, climate change impacts the number and diversity of pollinators due to the increased frequency and strength of extreme events including droughts, floods, and disruptions to crop flowering cycles (FAO, 2018a; Potts et al., 2010).

3.4.1.c Unlocking action towards SDGs related to pollinator decline

The UN Biodiversity Conference 2016 in Cancun recognized the contribution of pollinators to the SDGs, especially Goals 2, 3, 8 and 15. The global pollination crisis could potentially undermine the key aims of the 2030 Agenda for Sustainable Development (Agenda 2030): nourishing people and nurturing the planet. Pollinators play an essential role in producing food for a rising world population (SDG 2) and in maintaining biodiversity on land (SDG 15). Without pollinators, people's diets would be much less varied and more nutrient poor (Ellis et al., 2015), but proper nutrition and healthy diets are the number one factor that impact health outcomes (SDG 3), such as morbidity and mortality (Afshin et al., 2019). Pollinators are responsible for enabling conditions that support livelihoods for countless farmers worldwide (SDGs 1 and 8). Finally, some pollinators such as certain bee species provide products, i.e., honey, that are indispensable for local medicines and pharmaceutical industries globally (SDG 3).

3.4.2 Climate change and the overreliance on negative emissions technologies

3.4.2.a Case: negative emissions technologies as a climate fix

Global efforts to meet Paris Agreement targets – limiting the global average temperature increase to below 2°C, and pursuing efforts to limit the temperature increase to 1.5°C (UN, 2015) – will require anthropogenic GHG emission sources and sinks to be balanced by the second half of the century. The unavoidability of nonzero sources has led to the development of "negative emissions technologies" (NETs) where carbon dioxide is removed from the atmosphere through technological means (Anderson & Peters, 2016). NETs include bioenergy with carbon capture and storage (BECCS), afforestation and reforestation, direct air carbon capture and storage (DACCS), enhanced weathering of minerals, ocean fertilization and alkalinity enhancement, biochar as a soil amendment, and enhanced soil carbon sequestration (Fuss et al., 2018; Smith et al., 2016). Policymakers are informed by Integrated Assessment Models (IAMs), modelling the relationship between GHG emissions, effects of GHGs on climate, and the impacts of climate change; and these IAMs assume the large-scale use of NETs.

The effects of NETs need to be satisfactorily understood and addressed if NETs are to have a significant role in achieving climate goals. For example, implementing BECCS at the scale used in IAMs would compete with land for biodiversity and agricultural production (Dooley et al., 2018), and mass afforestation and reforestation may result in radiative forcing via decreased albedo at high altitudes and increased evapotranspiration, limiting effectiveness (Smith et al., 2016). Uncertainty exists around the performance of NETs in terms of large-scale carbon sequestration (such as the safe and underground storage of carbon - Fuss et al., 2014), their economic costs and lack of incentives (EASAC, 2018), and the social, economic, and environmental side-effects of their deployment (Buck, 2018; Fuss et al., 2018; Smith et al., 2016). Despite these uncertainties, NETs are still widely promoted and are legitimated through policy making (Beck & Mahony, 2017), but can remain imaginaries that are ‘buried’ in models (McLaren & Markusson, 2020). Anderson and Peters (2016) warn that over-confident reliance on large-scale use of NETs comes with a risk that society will be locked into a high-temperature pathway.

3.4.2.b Lock-in mechanisms

Current ‘transformational’ pathways towards emissions stabilization mainly focus on the practical sphere, including climate policies aimed at climate change adaptation, and deployment of ‘cost effective’ technologies such as carbon capture and geologic storage (O’Brien, 2018; O´Brien & Sygna, 2013; Thomson et al., 2011). Over-reliance on NETs – as a ‘technical’ or ‘spatiotemporal’ ‘fix’ (Boyd, 2017; Harvey, 2001; O’Brien, 2018) that promises to defer mitigation action (Carton, 2019) – constitutes a lock-in mechanism that in turn may divert attention from the extensive behavioural changes and societal reforms required to unlock sustainability transformations. The enthusiasm invested in (supposedly apolitical) NETs distracts from broader (and future) political action on climate mitigation efforts on the basis of ‘promised’ negative emissions (Markusson et al., 2017). Within this practical sphere, interventions produce results that can be measured, monitored and evaluated and are somewhat prioritized over actions in the political or personal spheres (O’Brien, 2018). Considering the interdependent and synergistic characteristics of the three spheres of transformation, prioritizing one at the expense of the other two can potentially hinder transformation.

A focus on NETs can also create a lock-in the political sphere by allowing for business as usual to continue, described in relation to “moral hazard” and “mitigation deterrence” in the context of solar radiation management (McLaren, 2016). For example, despite the promoted importance of NETs fixing carbon through soil and forest biomass, deforestation and soil degradation continue to add significant quantities of GHG emissions. The political sphere may see the formation, or persistence of lobby groups that defend the status quo and thus support NETs.

In the case of NETs, the political sphere is shaped by, and shapes, individual and collective beliefs reflecting ideologies that exclude alternatives on possible futures that include a radical restructure of consumption patterns. The promotion of, and fascination with the high-tech science of NETs also supports a ‘techno-optimism’ that could constitute a (conscious or subconscious) personal and collective coping strategy (of denial) whereby individual belief systems can go challenged (Barry, 2016).

3.4.2.c Unlocking action towards SDGs related to negative emission technologies

Addressing this lock-in requires recognition of climate change as requiring collective action across the personal, political, and practical spheres, rather than as a technological issue. Pursuing the mass deployment of NETs without adequate attention to environmental and social effects and unintended consequences, and obscuring the need for political action by overreliance on the practical sphere, may significantly undermine efforts to achieving SDG 13 (climate action). Addressing SDG 13 requires collective action across the three spheres of transformation, interacting with targets contained in SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible production and consumption), and SDG 15 (life on land). While lobby groups pushing for NETs may be persistent in the political sphere, there may be opportunities for alternative alliances such as the Climate Land Ambition and Rights Alliance (CLARA), rooted in social justice and agroecology, to emerge and push for ambitious social and technological innovations and more equitable governance of NETs.

3.4.3 Over-consumption globally with a focus on plastic pollution

3.4.3.a Case: plastic pollution

Plastics are resistant, versatile, lightweight, and cheap in comparison to alternative materials used for commercial purposes. They can be considered highly beneficial in supply chains, such as for packaging and food quality and safety and in construction and building. Plastic pollution, however, is one of the most significant environmental issues of the present day (IPBES, 2019). Despite existent attempts to incentivize a circular economy (e.g., led by the European Commission or the World Economic Forum) and some multi-lateral agreements concerning plastic pollution (e.g., led by the UN and related agencies), there is no global authority in charge of a sufficient solution to the problem (Nielsen et al., 2019).

Between 1950 and 2015, 600 Mt (9%) of the total estimated plastic waste was recycled, 800 Mt (12%) incinerated, and 4900 Mt were accumulated in landfills or in the natural environment, representing 79% of the waste material and, alarmingly, 60% of all plastic ever produced (Geyer et al., 2017). These patterns reveal a 10 times increase in plastic pollution since 1980 (IPBES, 2019). Additionally, only 100Mt of all the recycled plastics are currently in circulation, suggesting that recycling itself must also be considered with caution; only 10% of recycled plastic waste has been recycled more than once (Geyer et al., 2017).

Mismanaged plastic waste presents significant risk to pollute the environment, particularly plastic generated in coastal regions. In 2015, plastic waste in the oceans was estimated between 5.5 Mt to 14.6 Mt (out of a total of 36.5 mismanaged plastic waste), whilst in 2025 it is expected to increase from 10.5 Mt to 28 Mt (69.9 Mt in total). The projected figures of cumulative plastic waste entering the oceans by 2025 is shocking: between 92.8 Mt to 247.5 Mt (from a total of 618.7 Mt of mismanaged plastic waste - Jambeck et al., 2015). Even under optimistic and efficient scenarios for waste management, the total amount of plastic pollution will continue to increase in the absence of meaningful change (Lavers et al., 2019).

3.4.3.b Lock-in mechanisms

Powerful lock-in mechanisms in the practical sphere of transformation (O´Brien & Sygna, 2013) reinforce plastic pollution and/or prevent transformation towards sustainable trajectories. The persistent co-existence of increasing demand for plastics with poor waste management and ineffective policy (Lavers et al., 2019) are the core of the monumental scale of plastic pollution. The challenges behind designing reliable alternative materials to replace plastics, or the potential disruption caused by a complete ban in plastics, hinder structural transformation whilst the undesirable environmental impacts of plastic pollution increase (Neufeld et al., 2016). Additionally, developed countries tend to generate more plastic pollution per capita (Jambeck et al., 2015). In combination, the colossal, complex, and intertwined context of plastic pollution can also generate lock-ins in the personal sphere, ranging from the comprehension of the pollution's scale (e.g., risk perception) and the feasibility to develop plausible solutions (Lavers et al., 2019).

The amount of plastic pollution in the oceans and their physical properties reveal a lock-in in the political sphere not only for plastic pollution (impossibility of removing fragmented and durable materials from the oceans with current available technologies, especially in deep waters - Woodall et al., 2014) but also for other aspects linked to healthy marine ecosystems. Such aspects include human ingestion of contaminated fish, pollution that leads to over-exploitation of non-polluted fishing spots, or damaged environmental aesthetics causing negative impacts on tourism (Botero et al., 2017; Lavers et al., 2019). The lock-ins in this political sphere are particularly challenging in relation to quantity, quality, and time scales, limiting conditions for transformation. Removing plastics that are supposedly more easily accessible (an estimated 0.01 to 0.1 Mt of plastics in surface waters) cannot happen at a faster pace than annual pollution (up to 10 Mt). Also, the 'missing plastic' problem revealed by this discrepancy makes it very difficult or even implausible to track where plastic is accumulating (Cressey, 2016; Jambeck et al., 2015).

3.4.3.c Unlocking action towards SDGs related to plastic pollution

Strategies and collective actions aiming to unlock transformation towards sustainable states and trajectories need to integrate the three spheres of transformation (O'Brien, 2018). For example, taking in account citizens' conscious (e.g., education and training) and non-conscious (based on feeling and automatic associations, such as empathy for marine life) processes for behaviour change (Marteau, 2018) aligned with the SDGs 14 (Target 14.1: reduce marine pollution) and 12 (Target 12.5: substantially reduce waste generation) can influence all three spheres simultaneously. Embracing the existent lock-ins is also fundamental to avoid utopic and unrealistic aspirations: removing the current amount of plastic pollution in the oceans is impossible (Lavers et al., 2019). This does not justify the absence of clean-up, but rather accentuates the importance of investing in prevention of irreversible consequences from plastic pollution, including but not limited to: a) widespread bans on single-use items; b) waste management at the source, prioritizing action in areas with high levels of waste mismanagement (e.g., East Asia and the Pacific); and c) charges for plastic bags (Jakovcevic et al., 2014; Lavers et al., 2019; Rochman, 2016).

3.4.4 Over-consumption globally with a focus on meat consumption

3.4.4.a Case: Increasing meat demand for human consumption

Demand for animal products has resulted in livestock dominating over 83% of global farmland and accounting for 58% of food-related GHG emissions, despite providing only 37% of proteins and 18% of calories for humans (IPBES, 2019; Poore & Nemecek, 2018). Simultaneously, feed production covers a third of the global arable land and is responsible for 67% of agriculture driven deforestation (FAO, 2018b; Poore & Nemecek, 2018). The combination of livestock and total crop production (out of which ~36% is destined for feed) consumes roughly 75% of global freshwater resources (Cassidy et al., 2013; IPBES, 2019), and grazing covers ~25% of the world's ice-free land (and approximately 65 to 70% of drylands unsuitable for crop production). Although ruminants are estimated to convert 2.7 billion metric tons of grass into protein for human consumption, production methods and technologies currently used in this process lead to immense environmental impacts (Poore & Nemecek, 2018). Particularly, beef and mutton are by far the least efficient food products (i.e., by gram of protein produced) in terms of both land use (1.02m^2, followed by pork using 0.13m^2 in second place) and GHG emissions

(221.63gCO_2eq, whilst pork production emits 36.33gCO_2eq (Clark & Tilman, 2017). Altogether, producing 5% of calories from this source generates 40% of the environmental burden from global food production (Poore & Nemecek, 2018).

Meat provides high biological value proteins and essential micronutrients (such as iron and vitamin B12 - Development Initiatives, 2018; FAO, 2018b). However, excessive intake of red and processed meat poses risks for human health, particularly in high and middle-income countries. Health risks are associated with the carcinogenic properties of beef, pork, and lamb (Bouvard et al., 2015), and links between red and processed meat intake and mortality, morbidity, and increased rates of type II diabetes mellitus, stroke, and coronary heart disease (Afshin et al., 2019; Feskens et al., 2013; Larsson & Orsini, 2014). Production of animal feed can also lead to human and animal health impacts. Agricultural application of antibiotics has been associated with increasing levels of human antibiotic resistance, which can reveal serious limitations for conventional treatments of many communicable diseases (Landers et al., 2012). The health impacts from livestock farms are not only restricted to humans: waste can end up in marine systems and contribute to coastal eutrophication (i.e., abundant populations of algae stimulated by exposition to nitrates, which deplete water oxygen levels) and enteric methane fermentation can increase ocean acidification (its irreversible impacts in coral reefs, for instance, is well-documented - FAO, 2018b). The combined effect of this cascade of events can impair both the quantity and quality of marine life (IPCC, 2018).

3.4.4.b Lock-in mechanisms

Despite these well-documented impacts of overconsumption of meat, historical trends for the consumption of meat show a concomitant increase in per capita daily demand for meat protein with per capita GDP (Tilman & Clark, 2014). Taking into account increasing estimates of purchasing power in developing nations (especially in China) and of population growth, global demand for meat is anticipated to rise in the upcoming years (Springmann, Clark, et al., 2018; Tilman & Clark, 2014). These patterns present an important lock-in in the practical sphere of transformation (O´Brien & Sygna, 2013), since total protein demand also increased with income globally. Nonetheless, the lock-ins in the practical sphere are not restricted to increased demands, incomes, and populations. Farmers, for instance, experience different barriers to implementing new techniques and technologies in their operations. In a case of Estimated Breeding Values (EBVs – a breeding technique aimed to improve efficiency and consequently reduce GHG emissions), impediments to use EBVs were not only structural (e.g., lack of human resources on small farms) but also involved lock-ins in the personal sphere of transformation (e.g., failure to give credibility to the problem of GHG, conflicting objectives, or distrust in external expertise - Bruce & Spinardi, 2018).

Self-reinforcing lock-ins in the political sphere of transformation are revealed by some of the systemic consequences of the global demand for animal foods: emissions of methane from enteric fermentation, decreasing carbon dioxide sequestration potential from deforestation for pasture and feed, nitrous oxide exposition from feed production, or freshwater stress from overexploitation (FAO, 2017, 2018b; IPBES, 2019). Hypothetically, excluding animal products from human consumption could reduce 3.1 billion hectares of food's land use (a 76% reduction), 6.6 billion metric tons of CO_2eq (a 49% reduction), acidification by 50%, eutrophication by 49% and scarcity-weighted freshwater withdrawals by 19% (Poore & Nemecek, 2018). Surely, the opportunities for improvement in the personal, political, and practical sphere of transformation are substantial and current trends of meat consumption reiterate the importance and urgency to act. Even under ambitious scenarios of a synergistic combination of dietary changes, technological advances, and food loss and waste reduction under optimistic estimates of income and population growth, it will be considerably challenging to keep food systems within planetary boundaries in the near future (Springmann, Clark, et al., 2018).

3.4.4.c Unlocking action towards SDGs related to overconsumption of meat

Food-related SDGs are central for the achievement of many other SDGs (ICSU, 2017; Pradhan et al., 2017). Ensuring availability and access to nutritious food with quality and stability, for instance, is at the heart of SDGs 2 (all targets, such as 2.4 of 'sustainable food production and resilient agricultural practices' and 2.5 of 'maintain the genetic diversity in food production') and 3 (target 3.4 of "reduce mortality from non-communicable diseases and promote mental health" - Pradyumna, 2018). However, aiming to achieve those goals cannot impair the achievement of others. Trends in consumption of meat present immense threats at production and consumption stages to SDGs 6 (target 6.4 of 'increase water use efficiency and ensure freshwater supplies'), 12 (target 12.2 of 'sustainable management and use of natural resources'), and 15 (targets 15.1 of 'conserve and restore terrestrial and freshwater ecosystems', 15.2 of 'end deforestation and restore degraded forests', and 15.5 of 'protect biodiversity and natural habitats').

To achieve transformation towards sustainability, enabling conditions for collective action at multiple levels and scales is required, considering initiatives in synergy rather than isolated measurements. Some potential has been demonstrated for: (a) citizen and consumer changes (e.g. vegetarian, vegan, or flexitarian diets - Poore & Nemecek, 2018; Springmann, Clark, et al., 2018); (b) adequate food labelling and dietary guidelines (taking in account both human and planetary health - Khandpur et al., 2018; Ritchie et al., 2018); (c) tax on red and processed meat (Springmann, Mason-D'Croz, et al., 2018); (d) sustainable intensification of livestock (e.g., "carbon neutral beef" - Alves et al., 2017); (e) multi-stakeholder and multi-action frameworks for healthy diets from sustainable food systems (e.g., Nuffield Ladder of Policy Intervention), and (f) calls for platforms of international collaboration for scientific assessment and evidence-based institutions (e.g., IPCC-like intergovernmental panel for sustainable food systems or UN Framework Convention on Sustainable Food Systems - Willett et al., 2019). If applied in combination, these actions and their associated enabling conditions can address the lock-in mechanisms discussed here and improve current states and trajectories that reinforce vulnerabilities or hinder transformation towards sustainability.

3.5 Discussion

3.5.1 Summary of the analysis

Supplementary Table 3.1 (Appendix 3) provides a summary of our analysis in relation to the four case studies: pollinators decline, Negative Emission Technologies (NETs) fixation, plastic pollution, and meat overconsumption. We aim to operationalize a comprehensive understanding between the undesirable properties of resilience and their impact on mechanisms for transformations towards sustainability. Despite vast and robust information on the links between pollinator decline leading collapse of ecosystem services or overconsumption leading to burgeoning plastic waste in our oceans, human behaviours at all scales remain resistant to change. There is a gap in our ability to evaluate risks and connect emotionally to changes in the biosphere, understand how humans impact on the biosphere affects ourselves and others, and act to change structures, norms, values, and behaviours (Marteau, 2018). Even when the solutions are agreed upon there is a gap in feasibility, locked into undesirable states or trajectories.

The lack of understanding between lock-ins and transformations has raised the explicit question: How can we unlock transformation in relation to these lock-ins? These questions then quickly lead us to realize that for transformation to be feasible we cannot separate the anthropogenic and ecological aspects in social-ecological systems (Randers et al., 2018; Reyers et al., 2018). We need to think across multiple scales (i.e., dimensions used to measure and study any phenomenon, such as spatial, temporal, and jurisdictional) and multiple levels (i.e., the units of analysis that are located at different positions on a scale, such as globe, regions, landscapes, and patches for spatial scale - Cash et al., 2006). Whatever solutions designed to tackle problems might look like, they will be multidimensional (Donohue et al., 2016) in terms of essential variables, disturbance types, scales, and mechanisms. There can be no shortcut to transformation by focusing on single variables, scales, and mechanisms (Lade et al., 2017; Stirling, 2010). This integration is timely because of the increasing frequency of undesirable social-ecological traps (Boonstra, 2016).

3.5.2 Key lock-in mechanisms characteristics

To address our overarching question of: 'how can we understand lock-ins in order to break them for social ecological transformations?' we synthesize and discuss *three* critical elements across the four cases in this section. What are the main lock-in mechanisms characteristics? How is transformation trajectories or direction of change locked-in? Why, when, and how are critical shift factors unlocking transformations across scales?

Supplementary Table 3.1 (Appendix 3) presents the case-specific lock-ins across the personal, political, and practical spheres. Broadly speaking, at the personal level, lock-ins include ignorance, apathy, lack of empathy with non-humans, levels of risk perception, and cognitive dissonance. In the political sphere, profit maximization and market interests produce lock-ins and present barriers to collective action. In the practical sphere, certain development pathways create path dependencies which disincentivize alternatives and promote business-as-usual. The lack of connection between different spheres can strengthen lock-ins. For example, the perception of a lack of individual agency was common across the cases analysed: being ‘one individual’ acting in relation to global social-ecological challenges instils a feeling of alienation and precludes demand for political action in the political sphere. Likewise, a lack of action in the political sphere closes down sustainable alternatives for technologies and behaviours in the practical sphere. The personal, political, and practical spheres of transformation are thus interdependent. Actions to break these mechanisms require a number of enabling conditions which require convergence across the personal, political, and practical spheres of transformation (see Table 3.1). Given the interdependence of the spheres of transformation, convergence of these enabling conditions is critical to ensure that actions in one sphere are not prioritized over actions in another (as exemplified by a stronger focus on the practical sphere in climate change mitigation).

Table 3.1 – Key inter-locked mechanisms and enabling conditions towards sustainable development in the interdependent personal, political, and practical spheres of transformation.

Inter-locked mechanisms	Enabling conditions
Personal sphere of transformation	
• Adaptation before transformation: e.g., relying too much in the unknown benefits of a mitigation technology (e.g., NETs, ocean clean-up technologies) at the expense of changing the known causes of problems. • Profit maximization: predominant preference of increasing manufactured and financial capitals at the expense of social, human, and natural capitals. • Information disorders: rather than just absence of information (ignorance), it combines misinformation (false or misleading) and disinformation (false information that is purposely spread to deceive people) with elements of different preferences biases (confirmation bias, desirability bias, and selective exposure) (Lazer et	• Equitable sustainability: “*a shift in focus from individual elements and interactions, to system level dynamics and behaviour, advancing a social–ecological systems perspective through which both equity and sustainability are understood as intertwined drivers and outcomes of coupled systems dynamics*” (Leach et al., 2018). • Open up narratives: acknowledge the importance of the extensive behavioural changes and societal reforms required to unlock sustainability transformations. Ask the difficult but inevitable questions (e.g., who is included and who is excluded from decision-making? Who gains? Who loses? What to do with the winners and losers?). Expand the utilitarian view of capitals (e.g., more than commoditization of natural, social, and

al., 2018). Applications vary widely, from the media sector, marketing to democratic elections. • Cognitive dissonance: occurring between the personal and the practical spheres of transformation, it reveals the inconsistencies between the individual's beliefs, attitudes, and behaviours (Harmon-Jones & Harmon-Jones, 2007). In this study, we refer to cognitive dissonance that leads to the persistence of attitudes and behaviours impairing transformation towards sustainability.	human capitals). Explore beyond 'profit maximization', 'social-technical fixes', 'incremental adaptation', or 'social corporate responsibility'. • Trustworthiness: placing trust in trustworthy agents and activities. Expand the focus from generic attitudes and truth claims to evidence of honesty, competence, and reliability of commitments and competence (O'Neill, 2018). • Embrace the human condition: reflexivity and humility to acknowledge incomplete knowledge, the limitations of human cognition, and limited capacity to act (Stirling, 2010). Elements of risk, uncertainty, ambiguity, and ignorance ("*An overly narrow focus on risk is an inadequate response to incomplete knowledge*").
Political sphere of transformation	
• Economic expectations: a global debt-driven demand for perpetual expansion (Jackson, 2009). • Systemic tipping points and irreversible aspects of ecosystems: beyond certain critical thresholds under pressure, social-ecological systems can change in rapid, non-linear, unpredictable ways. Furthermore, overexploitation of some ecosystems services and functions can lead to irreversible consequences (e.g., risk of irreversible loss of many marine and coastal ecosystems due to climate change and pollution). • Diversion of attention: strategic combination of underestimation of the problem, focus shift to other irrelevant or incoherent topics, relativization of feasible alternatives, and manipulation of priorities (e.g., urgency over importance) designed to dissemble enabling conditions of transformation. • Inequity and injustice: in general, groups with limited capacity to adapt to the increasing risks are the least responsible for causing the problems across cases studies. In parallel, however, climate change policy tends to ignore these distinct impacts and policies to address them (Klinsky et al., 2017).	• Transparency and accountability: context specific, with promising impacts on emerging democracies and fragile contexts (Gaventa & McGee, 2013). 'Citizen-led' and 'social' accountability (in which it is ordinary citizens and/or civil society organizations who participate directly or indirectly in exacting accountability) show promising impacts in synergy with transparency (Increased transparency in state decision-making can facilitate greater accountability to citizens): improves the quality of governance, contributes to increased development effectiveness, and can lead to empowerment. • Anticipatory and preventive competence: strategic approach that encourages the precautionary principle applied to "*situations of scientific complexity, uncertainty and ignorance, where there may be a need to act in order to avoid, or reduce, potentially serious or irreversible threats to health and/or the environment, using an appropriate strength of scientific evidence, and taking into account the pros and cons of action and inaction and their distribution*" (EEA, 2013). • Diversification: including genetic and functional diversity for biosphere integrity (environmental aspects) and inclusive, competitive, and decentralized economy (economic aspects) have been shown to be related to enhanced resilience

	(Steffen, Broadgate, et al., 2015; Woodall & Shannon, 2018).
Practical sphere of transformation	
• Convergence of dominant powers towards profit maximization: economic elites and organized interest groups have been demonstrated to have substantial influence in policy making, independently of an average citizen's preferences (Gilens & Page, 2014). • Path dependencies and institutional inertia maintained by convergent powers: in addition to the inherent challenges of behavioural changes towards equitable sustainability (e.g., information disorders, cognitive dissonance, and diversion of attention), path dependencies and institutional inertia further encumber this process. • Scale of challenges: the states and trends reported for our case studies reveal the difficulty to implement reasonable actions aimed at solving the problems (e.g., plastic waste management can't cope with increasing production). • Nature of the problems: there is disagreement about the nature of the (interdependent) problems and about the solutions to them (i.e., wicked problems - Rittel & Webber, 1973). In addition, time is running out (delayed action also makes it more difficult and costly to break inertia towards desirable transformations), there is no central authority, those seeking to solve the problem might also be contributing to it, and policies favour short-termism rather than longer-term approaches (i.e., super wicked problems).	• Translation of the personal sphere into behavioural change: environmentally conscious (goal-directed, slow thinking) and non-conscious (feeling-oriented, fast, and automatic) encouragement and warnings for individuals to overcome cognitive dissonance (Marteau, 2018). In the case study of overconsumption of meat, for instance, making conscious the non-conscious nature of this behaviour (e.g., animal welfare and culture of meat), and changing a cue or a behavioural trigger in the environment (e.g., taxing red and processed meat) can be effective strategies (Springmann, Mason-D'Croz, et al., 2018). • Coherent policies and adaptive governance: inclusive (vast and complex problems in sustainability cannot be solved by a single individual or institution), appropriately selected and designed for the context, accounting for: a) underlying socioeconomic cause(s) of problems and their most important leverage points; b) efficiency and distribution of costs; c) resistance by powerful vested interests; d) effective jurisdiction and governance; and e) operation at both international and local levels (Sterner et al., 2019). • Collective action, leadership, and cross-sectional partnerships: initiatives and institutional reforms driven by the personal and practical spheres with inclusive collaboration from the civil society, business, government, and science, such as transdisciplinary science (Lang et al., 2012) and multi-stakeholder partnerships (Brouwer et al. 2015). Embedded leadership: "*one person can do it for a time, but several are better locally, regionally, and politically*" (P. Olsson et al., 2006). • Social-ecological resilience: from adapting to change to transforming for change (Reyers et al., 2018). In the normative sense, the ability to persist and sustain development in the presence of adversities. • Active sense of community: varying from engaging events, platforms for celebrating accomplishments and sharing experiences.

	Accessible and appealing communication, aligned with the listener vocabulary, next to the people on ground, encouraging protagonist participation of actors, and based on their real-world experiences in the right place and in the right time (e.g., rootedness: the power of place, community, and identity - K. Brown, 2015).

Abbreviations: NETs – Negative Emissions Technologies.

3.5.3 Enabling transformations across geographical and time scales

In this study we explored the relations between lock-in mechanisms and enabling conditions towards the UN SDGs in four case studies. As problems for sustainability and transformation science, joint challenge framing and collaborative definition of the research objects and boundaries were key elements in this study's design (Lang et al., 2012). These aspects, however, are highly dynamic and complex. Thus, to adequately translate results and propositions found in this study to 'real world' applications, careful definition of geographical and time scales must be distinguished for responses and impacts.

Efforts to decarbonise our economy, for instance, are not yet strong enough to overcome growing global energy demands (Le Quéré et al., 2018). If explicit cooperation to tackle GHG emissions had started in 2000, only a 4% reduction per year would be required to even this balance – in comparison to a more challenging 18% at the present day (Le Quéré et al., 2018). In addition, the multiplicity of drivers, actors, and resources can change substantially if a particular problem is being analysed in a small city or in a continental level. For example, pollinators decline in a specific region can be more easily tracked due to a possible change in the use of a pesticide impacting the reproductive cycle of a species. Global and continental changes in pollinator populations and their migration patterns due to industrial agricultural expansion or more frequent and extreme weather events, however, share common lock-in mechanisms with meat overconsumption and GHG emissions.

The complexity of lock-in mechanisms explored in this study are not only limited across geographical scales, but also across the case studies themselves. Climate change (as the main social-ecological problem behind the NETs fixation case study), for instance, creates a cascade of risks and impacts on multiple systems and sectors: land, livelihoods, biodiversity, human and ecosystem health, infrastructure, and food systems (IPCC, 2019). Furthermore, the effectiveness of many of the options used to sequester carbon are affected by the very problem that they are designed to address, for example, the capacity of natural climate solutions to sequester carbon decreases as climate change intensifies (IPCC, 2019).

In all case studies investigated, current states and trajectories of problems have not been reversed by proposed and implemented solutions. Due to the persistent growth associated with the cumulative nature of problems and the non-linear connections between exposure, impact, and response, insufficient or misdirected action can only expect to increase the complexity of lock-in mechanisms. In other words, despite particularities across different geographical and time scales, the longer socio-ecological systems are locked into unsustainable trajectories, the harder it is for transformational change to occur. Therefore, we argue that lock-in mechanisms ideally must be identified as early as possible to enhance the plausibility of overcoming complex challenges.

3.5.4 What are the key ‘real world’ lessons for unlocking SES transformations lock-ins

For a coherent and plausible operationalization, the enabling conditions elaborated in this study can only work in coexistent synergy. The three spheres of transformation are understood interdependently and in order: from personal, to political, and, lastly, to the practical domain (Sharma, 2007). In this sense, the same logic of cascade applied to interlocked mechanisms (i.e., persistent existence of vulnerabilities that can further reinforce other vulnerabilities and impair transformation) can be translated to support enabling conditions. This structural framework is essential to understand the plausibility to overcome lock-in mechanisms and also to embrace and encourage enabling conditions as plausible pathways.

We argue that understanding the elements related to the lock-in mechanisms and enabling conditions of social-ecological challenges can bring more benefits than focusing on specific case studies in isolation. We explored the case study of plastic pollution, for instance, as a serious environmental challenge, but this should not diverge attention from the key cause of plastic pollution: over-consumption. The importance of changing our individual behaviour or implementing technological fixes, in this sense, cannot obscure the fundamental need to transform our collective behaviour, political structure, economic systems, and underlying norms and values which are required to address intertwined social-ecological challenges, in this case, for achieving healthy marine environments (Nielsen et al., 2019). Embracing the enabling conditions as interdependent has the potential not only to improve the situation of plastic pollution in the oceans, but also to reduce the environmental impacts of other arguably larger problems, such as climate change and over-fishing (Stafford & Jones, 2019). In other words, our suggested enabling conditions do not compose a list of “pick and choose” elements to be deconstructed at will, but rather a “package” of potentially co-beneficial strategies for unlocking SES transformations lock-ins.

Aligned research approaches in sustainability transformation, such as the agenda of ‘leverage points’, also aim to understand the root causes of unsustainability and how to address them (Meadows, 1999). From a systems perspective, leverage points cover areas of potential intervention ranging from systems parameters and feedbacks, which are more tangible but limited in the impact of transformation (i.e., shallow leverage points), to systems design and intent, which are less obvious but can generate a potentially more impactful transformation (i.e., deep leverage points - Abson et al., 2017). Abson and colleagues argue that there is an urgent need to emphasize deep leverage points guiding humanity towards sustainability, specifically highlighting the priority to (i) reconnect people to nature, (ii) re-restructure institutions, and (iii) re-think how knowledge is created and used. In a complementary manner, we propose enabling conditions in this study to be guided by equity, inclusivity, and anticipatory values and principles. In other words, it is fundamental to evaluate the contextual elements and people's conditions before assuming generalizations or proceeding with interventions. In this sense, reflexivity and humility to acknowledge the implications for social cohesion is needed, for instance, if growth needs for a group of actors (cognitive, aesthetic, self-actualization, or transcendent needs) are being privileged at the expense of other people's needs (physiological, safety, belonging and love, and esteem needs - Koltko-Rivera, 2006).

Although we argue that the proposed enabling conditions are important for transformation towards sustainability to occur, they should not be framed as the solo determinants in the process of transformation. In the study of transformation to adaptive governance, Olsson *et al.* (2006) identified the importance of building knowledge, networking, and leadership as a preparation for change. Whilst navigating the turbulent and unpredictable phase of transition, the authors indicate the significance of flexibility and management of problems in different domains and across dynamic scales. Furthermore, a critical time for change (i.e., window of opportunity) is revealed between the two phases of preparation and transition, whereas *"... a problem is recognized, a* *solution is available, the political climate makes the time right for change, and the constraints do not prohibit actions*" (Kingdon, 1995). Finally, the emergence of shadow networks (i.e., informal networks that help to facilitate information flows, identify knowledge gaps, and create nodes of expertise) and of leadership are deemed as critical factors for transforming social-ecological systems (P. Olsson et al., 2006). In consonance with the enabling conditions described in our study, the phases and factors involved in the processes(es) of transformation towards equitable sustainability must be stressed for it to thrive.

We found that enabling conditions are well aligned with deep leverage points (Abson et al., 2017) in the three spheres of transformation that incorporate reflexivity on the multi-motivated and many times simultaneous needs of people to harness the potential of transformation towards equitable sustainability. It is essential to emphasize, however, that the enabling conditions proposed in this study should not be interpreted as an idealistic panacea for the problems in sustainability and transformation science. Rather than visualizing the enabling conditions as a master key designed to open all locks (i.e., lock-in mechanisms) which prevent transformation towards sustainability to occur, a more adequate analogy is to understand them as a chemical catalyst in a particular solution: they can facilitate reaction by providing an alternative reaction mechanism with a lower activation energy. In other words, they can unveil some of the intrinsic conditioning and determining factors in the intertwined relations among actors, networks, and behaviours of a particular context and their plausible solutions – rather than being framed or used as an extrinsic stimulus or 'exogenous shock' designed as big 'pushes' to break lock-in mechanisms. In poverty alleviation research, for instance, framing the factors that influence some of these parameters (i.e., enabling factors) have not only been shown to sustain inherent advantages over 'positive shocks' in one hand (Ngonghala et al., 2017), but can also incorporate synergistic benefits in the other (e.g., by emphasizing nature and culture of the problem or by revealing the potential of new opportunities for enabling conditions following transformative change - Lade et al., 2017). Therefore, we argue that encouraging an explicit attention to the enabling conditions can promote simultaneous and multiple benefits for sustainability and transformation science exploring tangible and plausible pathways towards sustainable development.

3.6 Conclusion

Addressing multiple interrelated SDGs will require action across interdependent personal, political, and practical spheres of transformation. In this study, we have operationalized an understanding of the lock-in mechanisms across serious social-ecological challenges that impede progress towards the SDGs, through an examination of case studies on pollinator decline, negative emissions technologies, plastic pollution, and increasing meat demand for human consumption. This analysis finds a range of common lock-in mechanisms relating to personal, political, and practical spheres. In the personal sphere, lock-in mechanisms include adaptation before transformation, profit maximization, information disorder, and cognitive dissonance. In the political sphere, economic expectations, ecosystem tipping points, diversion of attention, and inequity and injustice limit the capacity for meaningful shifts towards sustainability. In the practical sphere, convergence of dominant powers toward profit maximization, institutional inertia, the scales of the challenges and nature of the problems represent the key lock-in mechanisms to be addressed.

Facing these lock-in mechanisms with an action-oriented question might seem overwhelmingly implausible at first glance: what can we do about them? Once we deconstruct them and try to better understand their elements, however, we start to identify potential pathways for transformation. To address this question and herculean endeavour, we present a set of common enabling conditions needed to disrupt current states and trajectories, and to potentially shift them onto more equitable and sustainable pathways. These enabling conditions are, in the personal sphere, reflexivity and humility, trust, equitable sustainability, and opening up narratives. In the political sphere, enabling conditions include transparency and accountability, anticipatory and preventative competence, and diversification in ecological and social systems. Finally, in the practical sphere, enabling conditions that emerge include behaviour change, coherent policies, collective action, leadership, and cross-sectional partnerships, social-ecological resilience, and community. These enabling conditions must converge to start to unlock opportunities for sustainability transformation. While these enabling conditions cannot be viewed as an idealistic panacea for the social-ecological challenges, they provide lessons for sustainability and transformation science as they represent the conditions needed to develop tangible and plausible pathways towards sustainable development, Agenda 2030, and beyond.

3.7 Declarations

3.7.1 Conflict of interests

The authors have no relevant financial or non-financial interests to disclose. The funders of the study had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

CHAPTER 4

TRANSFORMATION ARCHETYPES IN GLOBAL FOOD SYSTEMS

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All co-authors contributed to article conceptualisation and writing. André Dornelles was responsible for data curation, visualisation and writing the original draft. André Dornelles, Tom Oliver, Ralf Seppelt, and Michael Denney designed the methodology, conducted the formal analysis, and verified the underlying data. André Dornelles and Tom Oliver contributed to funding acquisition and article supervision. All authors had full access to all data in the study and accept responsibility to submit this work for publication.

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4.1 ABSTRACT

Food systems are primary drivers of human and environmental health, but the understanding of their dynamic co-transformation remains limited. We use a data-driven approach to disentangle different development pathways of national food systems (i.e., ‘transformation archetypes’) based on historical, intertwined trends of food system structure (agricultural inputs and outputs and food trade), and social and environmental outcomes (malnutrition, biosphere integrity, and greenhouse gases emissions) for 161 countries, from 1995 to 2015. We found that whilst food systems have consistently improved in terms of productivity (ratio of output to input), other metrics suggest a typology of three transformation archetypes across countries: rapidly expansionist, expansionist, and consolidative. Expansionist and rapidly expansionist archetypes increased in agricultural area, synthetic fertiliser use, and gross agricultural output, which was accompanied by malnutrition, environmental pressures, and lasting socioeconomic disadvantages. Across all transformation archetypes, agricultural greenhouse gases emissions, synthetic fertiliser use, and ecological footprint of consumption increased faster than the expansion of agricultural area, and obesity levels increased more rapidly than undernourishment decreased. The persistence of these unsustainable trajectories occurred independently of improvements in productivity. Our model underscores the importance of quantifying the multiple human and environmental dimensions of food systems transformations to identify potential leverage points for sustainability transformations. More attention is thus warranted to alternative development pathways able of delivering equitable benefits to both productivity and to human and environmental health.

4.2 Introduction

Industrial agriculture arose as a defining feature of global food systems, revealed by increased total crop yields and higher yield per input at scale. Important progress in skills, technology, infrastructure, and trade has improved food productivity (i.e., output in terms of kg or kJ of food per unit of input invested - Benton & Bailey, 2019) and enabled the expansion of global, interconnected food supply chains. The widespread premise of prioritising yields and cheaper food to improve the human condition, however, has recently been under scrutiny due to its detrimental effects to sustainable development (Lindgren et al., 2018; Sukhdev, 2018). From a perspective of the Sustainable Development Goals (SDGs) framework, numerous synergies and trade-offs exist between the 17 goals and 169 targets for human well-being, economic prosperity, and environmental protection (Pradhan et al., 2017). Arguably, food systems are the entity that primarily connects good health and wellbeing (SDG 3), sustainable consumption and production (SDG 12), and life on land (SDG 15 - Pradyumna, 2018).

Global food systems have been failing to deliver adequate diets for everyone: an increasing prevalence of 9% of the global population is undernourished whilst, paradoxically, obesity currently affects more than 13 % of individuals (FAO et al., 2020) and roughly 1/3 of all food is lost or wasted (Aschemann-Witzel, 2016). Around 87% of all countries worldwide exhibit the coexistence of insufficient or excessive forms of malnutrition (Development Initiatives, 2020), and diet is the number one risk factor for mortality and morbidity worldwide (Afshin et al., 2019). In parallel, from production to consumption, food is responsible for 34% of anthropogenic greenhouse gas emissions (Crippa et al., 2021; Poore & Nemecek, 2018) and about 70% of freshwater use (Whitmee et al., 2015). Agriculture is the prime driver of the transgression of biosphere integrity and biogeochemical flow (e.g., nitrogen deposition - Campbell et al., 2017) and, in turn, is the sector most affected by these transgressions (IPCC, 2014).

The investigation of the complex and dynamic interactions driving the sustainability and efficiency of food systems from input to output remains a challenge (Hadjikakou et al., 2019; TEEB, 2018). Food research is often fragmented across academic disciplines and sectors, and production or consumption stages tend to be studied in isolation from one another (Campbell et al., 2016; Dornelles et al., 2020). If aspects of health, equity and sustainability are not embedded in a more comprehensive framework of food systems efficiency (i.e., 'the number of people that can be fed healthily and sustainably per unit input invested' - Benton & Bailey, 2019), a narrow focus on increased productivity has the potential to accelerate detrimental effects for planetary and human health in an increasingly connected world (Bahadur et al., 2018; Bengtsson et al., 2018; Seppelt et al., 2020; Willett et al., 2019). Critically, a clearer understanding of the magnitude and direction of trade-offs between food systems' productivity and key metrics is sorely needed for sustainability transformations (Fears et al., 2019; Nyström et al., 2019; Oliver et al., 2018; Pradhan et al., 2017). One way to achieve this, as we present in this study, is via an integrated model using standardized metrics to capture the multiple dimensions of food systems.

4.2.1 Transformation of global food systems

Whilst a focus on productivity of food systems has been elevated to a protagonist narrative (e.g., the claim that the world will need to produce 70% more food by 2050 has assumed unexpected traction - Alexandratos & Bruinsma, 2012; Benton & Bailey, 2019; Sukhdev, 2018), more holistic development pathways of multiple, coexisting environmental and social outcomes in global food systems are often unquantified. Such social-ecological links related to food tend to be reported either in the form of states or trajectories. The state of multiple environmental, social and economic indicators across food systems have been measured cross-sectionally at different times and spaces (Chaudhary et al., 2018; Zurek et al., 2018) by the impacts of specific food types (Clark & Tilman, 2017; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018), and/or by estimates of future production hotspots or of potential mitigation measures for biosphere integrity (Springmann, Clark, et al., 2018; Zabel et al., 2019). In contrast, longitudinal studies track variables through time and so offer a means to connect cause and effect, and to study trajectories. This approach has been used previously to study transformation pathways of food systems for pre-defined groups of countries (e.g., by areas of free trade or level of development - FAO, 2017), for quantifying the costs and economic returns of distinct agricultural models (Ruttan, 1977), for the exploration of mechanisms behind agricultural transitions (e.g., interactions between population growth and urbanization - Cumming et al., 2014), or for national food indicators of socio-economic access, biophysical capacity, and diversity of production (i.e., ‘resilience indicators’ - Seekell et al., 2017). As the availability of rich longitudinal datasets increases, so does the opportunity to: 1) gain an empirical understanding of intertwined rates of change within and across national food systems; 2) quantify the direction and magnitude of structure and outcome metrics under a comparable methodology; and thus to 3) specifically capture and compare the transformational feature of food systems.

4.3 Methods

4.3.1 Overview

Our data-driven approach to identify patterns of transformation (i.e., ‘transformation archetypes’) in global food systems analyses historical trends of structure metrics including agricultural inputs, outputs, and trade, and their relationship to outcomes including biosphere integrity, malnutrition (i.e., obesity and undernourishment), and greenhouse gases emissions in 161 countries, from 1995 to 2015. 'Transformation archetypes', in our study, reveal categorisations of patterns of incremental change that are suggestive of specific transition pathways, and the trajectories that these processes suggest or point to in terms of futures that may or may not be sustainable. This approach integrates statistical methods often used in ecology (e.g., cluster analysis and dissimilarity matrixes - Charrad et al., 2014) with macroeconomic measurements of trend analysis (e.g., Compound Annual Growth Rate; expressed as % of annual change and reported as median and interquartile range). Our analysis assumes broadly constant compound temporal rates, which is supported by an additional analysis of five-year intervals to explore potential short-term spikes. Our approach to map the resultant archetypes of food system change with respect to co-evolving environmental, social, and economic outcomes is valuable to help to investigate intertwined empirical links, track the speed of progress towards desirable social-ecological goals, and also reveal watchpoints to potentially mitigate risks associated with the existing undesirable trajectories of change (Dornelles et al., 2020).

Our analysis of transformation archetypes in global food systems consisted of three main stages (Supplementary Figure 4.1 – Appendix 4): 1) Data acquisition – extensive review and search; 2) Data preparation – standardization and duration filters applied; and 3) Data analysis – trend analysis, cluster algorithm, significance testing, and analysis of five-year intervals. All steps in data preparation and analysis were conducted in the software R version 3.6.1.

4.3.2 Data acquisition

We conducted an extensive search of publicly available repositories and official databases for comprehensive structure and outcome metrics expressing multiple aspects of agricultural production, food security and biosphere integrity related to food systems (Supplementary Table 4.1 – Appendix 4). Our design enabled a comparative assessment of the paradigms of interest: structure metrics are widely used as measurements of improved production (cf. *paradigm of productivity*), whilst the combination of structure and outcome metrics were here used to assess their links to productivity (cf. *paradigm of systemic efficiency* – Supplementary Figure 4.2 – Appendix 4).

Structure metrics expressed different aspects and practices related to agricultural production as a whole and related indicators of socioeconomic access, as follows: input (composed by agricultural area, synthetic fertilizer use, and agricultural employment), output (represented by gross agricultural output), productivity (quantified by Agricultural Total Factor Productivity Index), and economic metrics (constituted by food imports, food exports, and Producer Price Index of agriculture). Structure metrics, as such, reveal means to achieve the ultimate function of food systems (i.e., feeding people) or are related to them as drivers or elements. Outcome metrics accounted for specific and non-specific impacts of food systems products and/or activities in respect to biosphere integrity (expressed by the Red List Index), land-system change (covering forest area and Ecological Footprint of Consumption), malnutrition (composed by prevalence of adult obesity and prevalence of undernourishment), and greenhouse gases emissions (including agricultural GHGE, land-use change and forestry GHGE, and the sum of agricultural, forestry, and other land-use – AFOLU GHGE; Supplementary Table 4.1 – Appendix 4).

Outcome metrics, in this sense, express direct food-related goals for human and planetary health, proxy quantifications of such goals, and/or potential externalities from food practices. Socioeconomic indicators were represented by income category, GDP per capita (expressed as nominal and purchasing power parity), and the Human Development Index (expressed as index and category).

Data criteria for acquisition included attributes for length (minimum of 100 countries), time series (minimum of 10 years of measured observations, preferentially on a yearly basis), and relevance to multiple food systems stages. Twelve databases were explored from which 36 different metrics were acquired, respecting these selection criteria and described in more details in the Supplementary Tables 4.2 and 4.3 (Appendix 4). Metadata for all metrics are available in the Appendix 4.

4.3.3 Data preparation

The metrics acquired were subsequently collated into a hierarchical (i.e., individual variables, derived variables, and aggregate indicators) and standardized format by ‘country’, ‘year’, and ‘value’ for the longitudinal analysis. Instead of using conventional units for the state of a metric (e.g., hectares for spatial coverage, % of employment for agricultural work, or indexes for aggregated indicators), we expressed our data as annual change rate to enable a normalised comparison between distinct metrics and to specifically capture the transformational element of food systems (more details in ‘trends analysis’). We took precautions to prevent double-counting across the different hierarchies of our structure and outcome metrics. For structure metrics, we investigated how the patterns of change of raw (e.g., agricultural area) and proportional variables (e.g., agricultural employment) helped to explain wider patterns of change in one aggregate indicator in which they are embedded (e.g., productivity, TFP). All structure metrics were previously scaled and tested for correlations before the analysis of rates of co-transformation across countries (more details in ‘cluster algorithm’). For outcome metrics, we explored the links between the emergent development pathways found across countries with changes in: a) specific food-related impacts (e.g., malnutrition); b) externalities tied to changes in structure metrics (e.g., biosphere integrity), and c) different components of such pressures (e.g., agricultural GHGE, land-use change and forestry GHGE, and AFOLU GHGE).

The filters and duration analysis were conducted for each metric in two steps: a) an initial filter designed to collate the metrics which met the initial criteria for acquisition (data for ≥100 countries and ≥10 years of observations) after the standardization stage; and b) a refined filter programmed to extract maximum number of countries with comparable durations (i.e., number of years) and periods (i.e., in a similar time coverage) across the remaining metrics following the initial filter, covering at least 80% of the possible maximum duration for that respective window of time (see Appendix 4; Supplementary Tables 4.4 and 4.5). In other words, the refined filter of best fit analysis was intended to assemble the metrics by the most reasonable chronological consistency, and thus avoid anachronic comparisons in duration (e.g., comparing the annual growth rate of 12 years of measured observations of one particular country with 40 years of data points of a different country) or period of coverage (e.g., juxtaposing the annual growth rate of one country from 1961 to 1981 with another country from 1991 to 2011).

4.3.4 Data analysis

Our data analysis consisted of four steps: (a) trend analysis, (b) cluster algorithm, (c) significance testing, and (d) analysis of five-year intervals.

4.3.4.a Trend analysis

The trend analysis was designed to assess the patterns of transformation per year in all structure and outcome metrics across countries. Following the filter of best fit indicated in the data preparation stage, the timeframe for evaluation and comparison of metrics was stipulated for the period from 1995 to 2015. In our model, we adapted the widely used equation of compound annual growth rate to estimate annualized trends in all metrics (Prajneshu & Chandran, 2005). Whilst there might exist legitimate foundations for criticism on the use of empirical models assuming linear change over time (Paine et al., 2012; Prajneshu & Chandran, 2005) we understand that the adjusted equation and subsequent analysis of five-year intervals sufficiently address any potential limitations of our approach. In addition, the use of the adjusted compound annual change rate can facilitate comparison amongst multiple metrics which show varying longitudinal paths while enabling a standardized expression of change across numerous countries. The adapted equation of compound annual change rate, expressed as % of annual change (reported in the results as median and interquartile range), was calculated taking into account the median of the first five *starting values* and the last five *end values* in order to prevent undue weight of first and last years:

$$End\ value = \ median\ (last\ five\ end\ values)$$

$$Start\ value = \ median\ (first\ five\ start\ values)$$

$$CACR = \left(\frac{End\ value}{Start\ value}\right)^{\left(\frac{1}{End\ value\ (Year) - Start\ value\ (Year)}\right)} - 1\ \times\ 100$$

4.3.4.b Cluster algorithm

The cluster analysis computed patterns of co-transformation in five key structure metrics: agricultural area, synthetic fertilizer use, agricultural employment, gross agricultural output, and Agricultural Total Factor Productivity. These five metrics were included as the key structure metrics because of their: a) key importance to assess the input and production stages of food systems from the paradigm of productivity; b) relative low variance in comparison to other structure metrics (e.g., expressed by current monetary units); c) well-established use across different disciplines in the food literature to assess different components and the efficiency of agricultural production (i.e., ratio of output per unit of input – productivity); and d) independence (i.e., no strong pair-wise correlations were identified for the rate of change between all the five structure metrics – all Pearson's correlation scores < 0.6).

Due to substantial variation in contextual drivers and states of the five key structural metrics of food systems across countries globally, we investigated potential similarities in their longitudinal change using a cluster analysis approach to be able to identify transformation archetypes. For this purpose, we used the R package *NbClust* (Charrad et al., 2014), which estimates the most appropriate clustering scheme and determines the number of groups for a set of different objects. The cluster algorithm runs 30 indices simultaneously, in addition to hierarchical clustering with different distance measures and aggregation methods and obtains the final result by varying all of their possible combinations. Before running the cluster analysis, we scaled the compound annual change rate of the five key structural metrics by their respective median and median absolute deviation and tested for collinearity to minimize the potential dominance of a particular set of metrics over others due to its magnitude, unit, or range. Finally, the metrics were merged into the same data frame by their scaled compound annual change rate values and only the countries with existing values for all five key structure metrics were included in the assessment by the cluster algorithm (leading to 161 countries in total). To generate the cluster dendrogram, the Euclidean distances of the dissimilarity matrix across all possible ordering of observations (2^{n-1}) were used as input for the hierarchical cluster method (Ward2), which agglomerated the tightest cluster scheme possible and placed observations in order by the square root of the weighted sum of their squared distances.

4.3.4.c Significance testing

Following the allocation of countries into different groups of transformation archetypes provided by the cluster analysis, we tested for statistical differences across groups for all structure and outcome metrics by an analysis of variance model, after the implementation of the Shapiro-Wilk test of normality. Tukey's honest significance test was applied to scrutinize differences between specific groups. Statistical significance threshold was set at 0.05.

4.3.4.d Five-year intervals analysis

As a final step, we assessed the potential for non-linearities in the temporal trends of the food system metrics used in our analysis to influence allocation of transformation archetypes. To this end, we computed the compound annual change rate of all structure and outcome metrics of each transformation archetype in sub-divided periods of five years: from 1995 to 2000; from 2000 to 2005; from 2005 to 2010; and from 2010 to 2015. Here, however, we used the conventional compound annual change rate equation of real end and start values for each five-year interval (and not the median of the first five start values and last five end values).

Goodness of fit statistics were calculated to explore potentially more appropriate cluster composition (guided by the same absolute number of clusters reported in the main results from 1995 to 2015). Within and across cluster distances (Ward2) were extracted and the cophenetic distance was calculated to express goodness of fit (correlation between

Euclidean distances in the dissimilarity matrix and the agglomeration output from the hierarchical cluster, Ward2). The cophenetic distances were broadly similar in the five-year intervals and in the main interval from 1995 to 2015 for the three transformation archetypes assessed.

4.4 Results

4.4.1 Archetypes of change

We identified three transformation archetypes in global food systems metrics from 1995 to 2015, as described in Box 4.1: 1) rapidly expansionist transformation archetype (RETA), 2) expansionist transformation archetype (ETA), and 3) consolidative transformation archetype (CTA). Evidence for the existence of three distinct transformation archetypes emerged more consistently than any other clustering across 30 different clustering indices tested (see 4.3 Methods), with significant differences in trend metrics between the clusters supported by a post-hoc ANOVA analysis (Supplementary Tables 4.6 and 4.7 – Appendix 4). In mapping the archetypes, we found coexistence of the three distinct transformation archetypes in neighbouring countries from South America, Sub-Saharan Africa, and South-western and South-eastern Asia (i.e., broad geographic regions are not homogeneous but show all three identified archetypes in close proximity; Figure 4.1). More detailed results are available in the Appendix 4, from the interpretation of the cluster algorithm's output (Supplementary Figures 4.3, 4.4, 4.5, 4.6, and 4.7 – Appendix 4) to five-year intervals analysis (Supplementary Figures 4.8 and 4.9 – Appendix 4). Below is a high-level summary of the key results.

Box 4.1 – Characteristics of the transformation archetypes in global food systems.

Rapidly expansionist transformation archetype (RETA): countries in RETA tended to show patterns of rapid expansion in agricultural area, synthetic fertiliser use, and gross agricultural output, whilst rates of change in structure and outcome metrics commonly surpassed values of 3% per year. These patterns of rapid expansion tended to be accompanied, however, by undesirable systemic outcomes including increases in obesity, agricultural greenhouse gases emissions, and ecological footprint of consumption. The 26 countries of this archetype were most commonly from Sub-Saharan Africa and South-eastern Asia. This archetype was predominantly composed of low-income countries in 1995 (n=19, 73%) and exhibited the lowest improvement in their socioeconomic status by 2015 (n=8, 30.8%).

Expansionist transformation archetype (ETA): this archetype often expressed intermediary rates of change between RETA and CTA, commonly surpassing rates of change of 1.5% annually. The 63 countries of this archetype were found across Asia, Africa, and Central and South America, but not North America or Western Europe. Many countries in ETA were of low and lower-middle-income category (n=30 and n=27, 48% and 43%, respectively) and 29 of them (46%) improved their socioeconomic condition by 2015.

Consolidative transformation archetype (CTA): CTA frequently indicated relative stability in outcome metrics (e.g., rates of change commonly between - 0.5 and 0.5% per year) and the lowest rates of change in key structure metrics across transformation archetypes. Many of the 72 countries of this archetype were from North America and Europe, although some were from South America and Eastern Asia, whilst a couple of nations were from Oceania and Northern and Southern Africa. CTA expressed not only the highest ratio of high-income countries (n=27, 37.5%) but also of income category improvement (n=37, 51.4%).

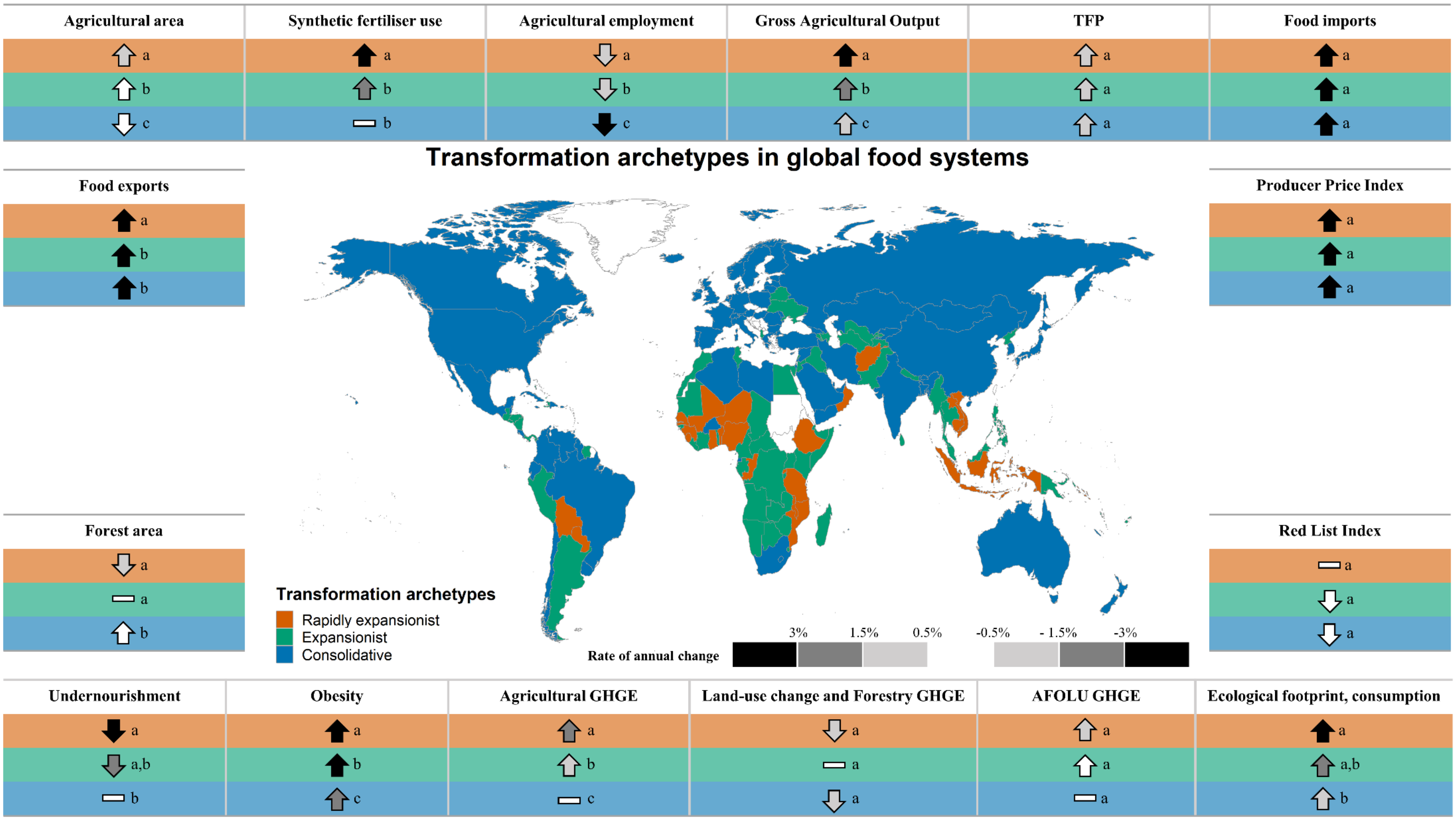
Transformation archetypes in global food systems
Agricultural area
a
b
c
Synthetic fertiliser use
a
b
b
Agricultural employment
a
b
c
Gross Agricultural Output
a
b
c
TFP
a
a
a
Food imports
a
a
a
Food exports
a
b
b
Producer Price Index
a
a
a
Forest area
a
a
b
Red List Index
a
a
a
Transformation archetypes
Rapidly expansionist
Expansionist
Consolidative
Rate of annual change
3%
1.5%
0.5%
-0.5%
- 1.5%
-3%
Undernourishment
a
a,b
b
Obesity
a
b
c
Agricultural GHGE
a
b
c
Land-use change and Forestry GHGE
a
a
a
AFOLU GHGE
a
a
a
Ecological footprint, consumption
a
a,b
b

Figure 4.1 (continued from previous page) – Transformation archetypes affecting national food production and supply of 161 countries from 1995 to 2015. Rate of annual change for structure metrics (on the top) and for outcome metrics (on the bottom) are measured by compound annual change rate (median, % / year). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). Arrows pointing up show increasing trends, arrows pointing down show decreasing trends, whilst white rectangles indicate no change over time. The colouring scheme expresses magnitude of the rates of change: black colour designates rapid change (≥ 3% and ≤ -3%), dark grey colour reveals intermediate (1.5% to 3% and -1.5 to - 3%), grey colour specifies mild (0.5% to 1.5% and -0.5% to -1.5%), whilst white colour represents slow change (0% to 0.5% and 0% to -0.5%). Abbreviations: TFP – Agricultural Total Factor Productivity; GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.

4.4.1.a Agricultural productivity

Our analysis suggests substantial progress from a perspective of food production and agricultural cost-efficiency over the past two decades. Improvement in Agricultural Total Factor Productivity was evident across all transformation archetypes, identified by similar annual rates of change reported as median and interquartile range (in between brackets): RETA = 0.82% (1.56%), ETA = 1.2% (2.16%), and CTA = 1.36% (1.29%). Agricultural area, synthetic fertiliser use, and gross agricultural output displayed the largest rates of annual change in RETA followed by ETA then CTA (with exception of synthetic fertiliser use, which showed similar trends between ETA and CTA; Figure 4.2). Importantly, no distinctions were found across transformation archetypes in terms of agricultural area at the beginning of the analysis, expressed by percent of total land composed of agriculture: RETA = 32.44% (11.98%), ETA = 39.98% (12.23%), and CTA = 42.45% (14.38%), suggesting that trends are independent of starting baseline of the archetypes. Agricultural employment was under the steepest annual reduction in CTA, declining -3.11% (1.79%) per year, and decreased further in RETA, -1.16% (1.62%), than in ETA, -0.65% (1.07%). Agricultural Total Factor Productivity was the only metric amongst the key structure metrics to show no differences across the three transformation archetypes, increasing at a rate of approximately 1% per year. This progress in productivity is widely assumed to bring wider socioeconomic benefits (Benton & Bailey, 2019; Matsuyama, 1992), however, our analysis shows it does not reliably reflect achievements across food systems in terms of environmental sustainability, overcoming coexistent forms of malnutrition, or improvement of socioeconomic wellbeing (Benton & Bailey, 2019; Matsuyama, 1992; Seppelt et al., 2020).

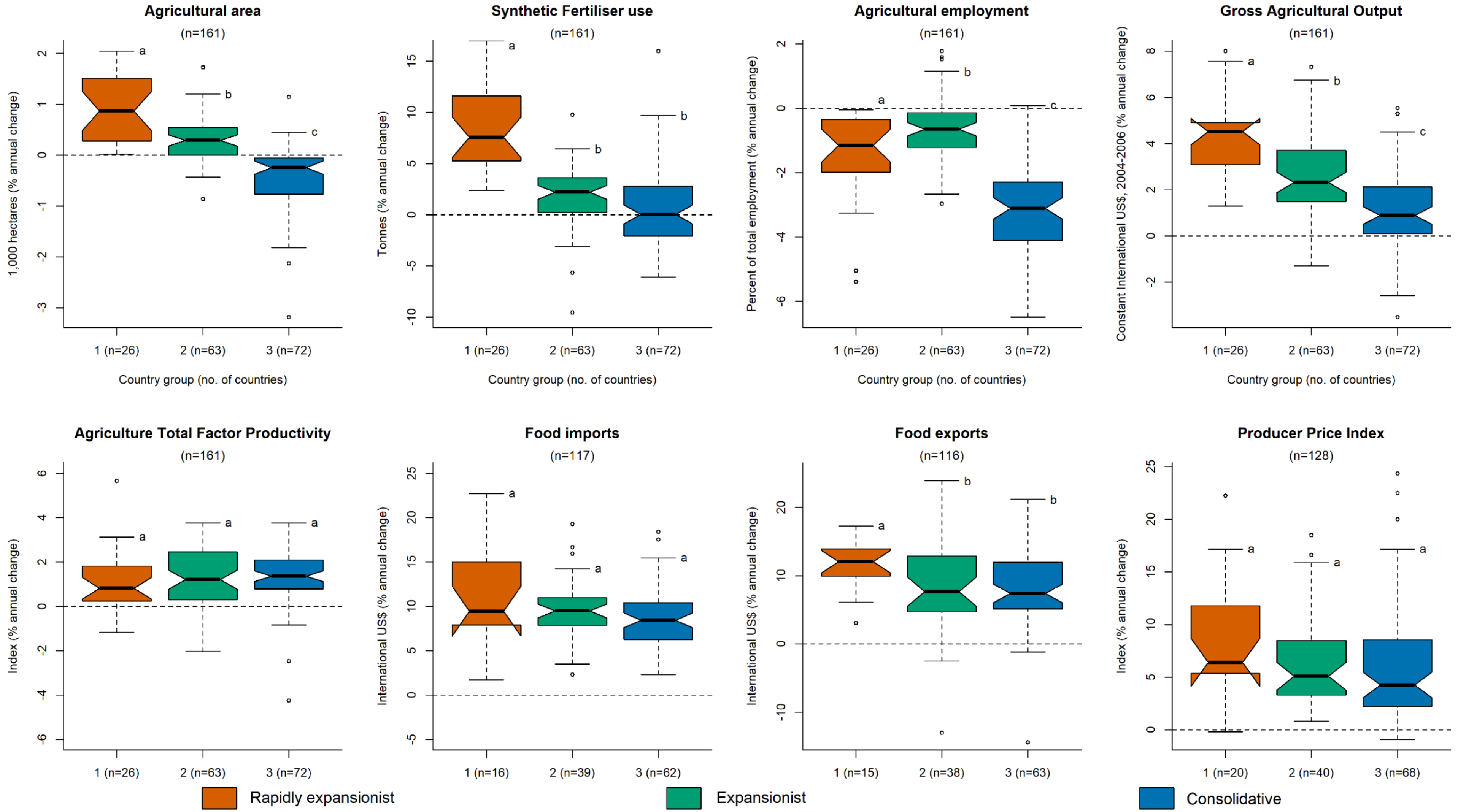
Agricultural area
(n=161)
1,000 hectares (% annual change)
2
1
0
-1
-2
-3
a
b
c
1 (n=26)
2 (n=63)
3 (n=72)
Country group (no. of countries)
Synthetic Fertiliser use
(n=161)
Tonnes (% annual change)
15
10
5
0
-5
-10
a
b
b
1 (n=26)
2 (n=63)
3 (n=72)
Country group (no. of countries)
Agricultural employment
(n=161)
Percent of total employment (% annual change)
2
0
-2
-4
-6
a
b
c
1 (n=26)
2 (n=63)
3 (n=72)
Country group (no. of countries)
Gross Agricultural Output
(n=161)
Constant International US$, 2004-2006 (% annual change)
8
6
4
2
0
-2
a
b
c
1 (n=26)
2 (n=63)
3 (n=72)
Country group (no. of countries)
Agriculture Total Factor Productivity
(n=161)
Index (% annual change)
6
4
2
0
-2
-4
-6
a
a
a
1 (n=26)
2 (n=63)
3 (n=72)
Food imports
(n=117)
International US$ (% annual change)
25
20
15
10
5
0
-5
a
a
a
1 (n=16)
2 (n=39)
3 (n=62)
Food exports
(n=116)
International US$ (% annual change)
20
10
0
-10
a
b
b
1 (n=15)
2 (n=38)
3 (n=63)
Producer Price Index
(n=128)
Index (% annual change)
25
20
15
10
5
0
a
a
a
1 (n=20)
2 (n=40)
3 (n=68)
Rapidly expansionist
Expansionist
Consolidative

Figure 4.2 (continued from previous page) – Global trends in structure metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data observations beyond the extremes of the whiskers. Horizontal dashed lines represent absence of change (i.e., 0% annual change rate). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). The transformation archetypes are coloured as: rapidly expansionist in vermillion, expansionist in green, and consolidative in blue.

4.4.1.b Environmental outcomes

Concurrent with the highest rate of increase in agricultural area, RETA exhibited the greatest magnitude of change in agricultural greenhouse gases emissions (GHGE), and ecological footprint of consumption, followed by ETA, whilst CTA tended to indicate comparative stability at high absolute impact levels (Figure 4.3). RETA and ETA displayed increasing rates of agricultural GHGE of 2.42% (1.87%) and 1.01% (1.68%), respectively, whilst CTA expressed virtually no change (despite showing decreasing rates of agricultural area). Ecological footprint of consumption increased more rapidly in RETA – 3.05% (1.47%) – in comparison to CTA – 0.99% (3.08%). Two metrics had unclear overall changes due to high variability across countries from 1995 to 2015 (GHGE from land-use change and forestry and from Agriculture, Forestry and Other Land Use – AFOLU; Supplementary Tables 4.6 and 4.7 – Appendix 4). The CT archetype manifested a higher rate of change than RETA and ETA in just one environmental outcome — forest area — with the highest increasing rate of change in this metric.

The Red List Index exhibited slow decrease averaged across all transformation archetypes of roughly -0.3% per year. More comprehensive assessments of biodiversity relevant to food and agriculture (e.g., pollinators, coral reefs, and soil-dwelling organisms) have reported substantial declines in vital ecosystem services over past decades, but comprehensive country level data are lacking (Beckmann et al., 2019; Pilling et al., 2020). Given the evidence of excessive chemical inputs in disrupting biogeochemical cycles (Campbell et al., 2017; Fowler et al., 2013), it is important to note the steady, high use of synthetic fertilizer in CTA and its steeply increasing use in RETA (and to some extent in ETA). CTA used an order of magnitude more synthetic fertiliser in absolute value in 1995 than ETA, and two orders of magnitude more than RETA: CTA = 2.2×10^5 (9.5×10^5) tonnes, ETA = 2.3×10^4 (16.3×10^4), and RETA = 9×10^3 (3.8×10^4). Thus, the absence of environmental pressure alleviation in CTA in combination with rapid agricultural intensification and expansion of agricultural area (strongly implicated in habitat loss and biodiversity decline - Schipper et al., 2020) in RETA, and to a slightly lesser extent in ETA, draw a worrying picture of the negative environmental impacts of recent global food system transformations.

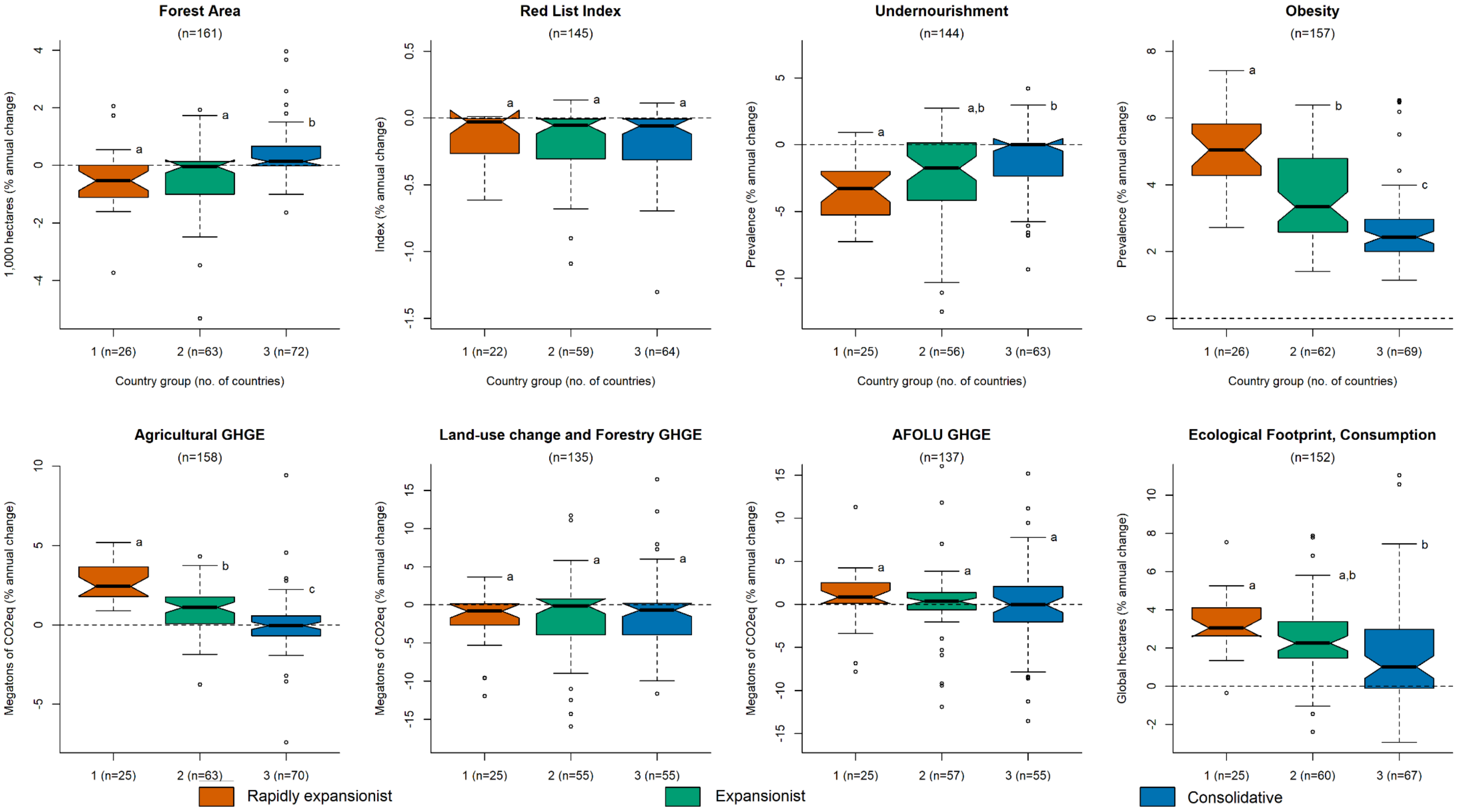
Forest Area
(n=161)
1,000 hectares (% annual change)
1 (n=26)
2 (n=63)
3 (n=72)
Country group (no. of countries)
Red List Index
(n=145)
Index (% annual change)
1 (n=22)
2 (n=59)
3 (n=64)
Country group (no. of countries)
Undernourishment
(n=144)
Prevalence (% annual change)
1 (n=25)
2 (n=56)
3 (n=63)
Country group (no. of countries)
Obesity
(n=157)
Prevalence (% annual change)
1 (n=26)
2 (n=62)
3 (n=69)
Country group (no. of countries)
Agricultural GHGE
(n=158)
Megatons of CO2eq (% annual change)
1 (n=25)
2 (n=63)
3 (n=70)
Land-use change and Forestry GHGE
(n=135)
Megatons of CO2eq (% annual change)
1 (n=25)
2 (n=55)
3 (n=55)
AFOLU GHGE
(n=137)
Megatons of CO2eq (% annual change)
1 (n=25)
2 (n=57)
3 (n=55)
Ecological Footprint, Consumption
(n=152)
Global hectares (% annual change)
1 (n=25)
2 (n=60)
3 (n=67)
a
b
c
a,b
Rapidly expansionist
Expansionist
Consolidative

Figure 4.3 (continued from previous page) – Global trends in outcome metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data points beyond the extremes of the whiskers. Horizontal dashed lines represent absence of change (i.e., 0% annual change rate). Lowercase letters 'a', 'b', and 'c' besides arrows indicate significant differences from the rapidly expansionist transformation archetype (baseline reference expressed by 'a') for each metric at $p < 0.05$ (e.g., 'a', 'a', and 'a' denote no difference across transformation archetypes whilst 'a', 'b', and 'c' indicate that all are different). The transformation archetypes are coloured as: rapidly expansionist in vermillion, expansionist in green, and consolidative in blue. Abbreviations: GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.

4.4.1.c Malnourishment

Improvement of yields and agricultural intensification have been widely encouraged to nourish a growing global population (Alexandratos & Bruinsma, 2012; Benton & Bailey, 2019), yet we found this paradigm has had only partial success in terms of mitigating coexistent forms of obesity and undernourishment over the past 20 years. Levels of undernourishment decreased substantially in the rapidly expansionist archetype and moderately in the expansionist archetype, by median rates of -3.27% (3.26%) and -1.77% (4.21%) annually, respectively (Figure 4.3). This pattern reveals remarkable progress, for instance, towards ending hunger in countries that have been most affected by food insecurity – the prevalence of undernourishment in 1995 in RETA and ETA countries was 24.7% (20.4%) and 18.7% (19.1%), respectively. The rate of obesity increase, however, surpassed the rate of undernourishment decrease in all archetypes. Increases in obesity were steepest in RETA, with growing prevalence of 5.04% (1.44%) per year, followed by the ETA with 3.34% (2.19%) and 2.42% (0.97%) for CTA. Note that RETA starts from a lowest base, with obesity prevalence in 1995 in RETA, ETA and CTA respectively as 3.25% (2.6%), 8.75% (1.45%), and 15% (5.7%).

These paradoxical trends in undernourishment and obesity reveal an important challenge for the majority of countries globally, since 87% of nations currently experience double or triple burdens of malnutrition (revealed by different combinations of overweight & obesity, underweight, and/or micronutrient deficiency - FAO et al., 2019). This is particularly relevant to countries that were not able to eliminate the substantial health and social challenges from food insecurity, such as those in South America, Sub-Saharan Africa, and South-western and South-eastern Asia (Figure 4.1). Simultaneous increases in obesity indicate high-levels of inequality in access to food and can overburden health systems in the pursuit of adequate prevention and treatment of non-communicable diseases attributable to dietary risks (Development Initiatives, 2020). An additional consideration is the systemic effects of an increasingly interconnected global food system, whereby rapid increases in both food imports and exports across the globe suggests a pattern of increased trade dependency. Food imports increased for all archetypes by roughly 10% annually (the highest rates of change recorded across all metrics), accompanied by an equivalent increase in food exports (highest values in RETA; Figure 4.2). This pattern can be seen as a double-edged sword: it can bring efficiency through comparative advantage, monetary gains for actors involved in global markets, and food diversity for many globally (Clapp, 2017); yet trade dependency has also been suggested to be associated with potential systemic risk to shocks (especially in major export-oriented countries with less diversity in food production - Kummu et al., 2020), and with consequent threats of undermining progress in undernourishment of populations most vulnerable to price fluctuations.

4.4.1.d Socioeconomic indicators

The rate of change of GDP socioeconomic indicators tended to be independent from the transformation archetypes (Supplementary Tables 4.6 and 4.7 – Appendix 4). All transformation archetypes showed a general trend of improvement in GDP per capita both for nominal and purchasing power parity: RETA = 3.5% (10.3%) and 2.5% (20.4%), ETA = 1.9% (13.1%) and 2.1% (10.2%), and CTA = 2.8% (9.5%) and 2.1% (7%). In terms of human development category (i.e., low, medium, high, or very high human development), RETA expressed, simultaneously, the biggest proportion of countries categorized as low human development in 1995 (n=17; 81%) and the lowest ratio of improvement in human development category by 2015 (n=7; 33.3%). ETA had a substantial proportion of countries in low and medium human development category at the beginning of the analysis (n=25 and n=20; 53% and 42.6%, respectively) and around two thirds of these countries showed improvements in their category at the end (n=30). CTA, finally, exhibited the highest proportion of countries in high and very high human development categories in 1995 (n=18 and n=19, 27.3% and 28.8%, respectively) and was tied with ETA in terms of improvement of category by 2015 (n=41, 62%). The Human Development Index was an exemption to this general trend in socioeconomic metrics, revealed by a steeper improvement in RETA than in ETA, followed by CTA: median of 1.57% (0.95% interquartile range), 0.97% (0.52%), and 0.67% (0.39%), respectively (Supplementary Tables 4.6 and 4.7 – Appendix 4). Although only 135 countries were measured for this metric, the proportion falling into the three respective archetypes was broadly equivalent to the full dataset: RETA = 21 (15.5%), ETA = 48 (35.5%), and CTA = 66 (49%) countries.

Economic development, traditionally measured by income level (i.e., low, lower-middle, upper-middle, and high-income countries stratified by gross national income per capita), was also found to be in a converse trajectory of change to RETA and ETA. Similar to the pattern for human development category, RETA not only had the highest proportion of low-income countries in 1995 (n=19, 73%), but also only 8 out of 26 countries (30.8%)

improved their income category by 2015. Conversely, CTA displayed the highest ratio of upper-middle and high-income countries early in the analysis (n=13 and n=27, 20.6% and 37.5%, respectively) and, simultaneously, showed the largest improvement in income category (n=37, 51.4%). The ETA had a substantial share of countries in the low and lower-middle-income category in 1995 (n=30 and n=27, 47.6% and 42.8%, respectively) and 29 out of 63 countries (46%) improved their condition by 2015. Overall, this means that expansionist traits exhibited by archetypes of change in global food systems did not broadly reflect increased incomes (i.e., GDP per capita) and, in more practical socioeconomic terms (i.e., comparable categories of gross national income per capita), tended to be associated with persistent socioeconomic disadvantages despite improved agricultural productivity.

4.5 Discussion

Our findings add quantitative evidence to recent qualitative assessments on food systems transformation to show that despite improvements in yields and productivity, national food production and supply across the countries investigated are in general failing to reorient their trajectories towards the ability to nourish people with healthy and sustainable diets per unit input (Bahadur et al., 2018; Benton & Bailey, 2019; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018; Willett et al., 2019). Our study reveals the extent of the historical and current trade-offs between food system productivity and more holistic measures of food systems sustainability and success in delivering environment, health and other social outcomes, including how this relationship diverges across countries.

Our study was designed to expand the assessment of emerging patterns in global food systems beyond linear assumptions of change over time or multidimensional analysis of single surrogate outcomes. We consequently paid crucial attention in the selection of metrics to quantify links amongst agricultural productivity, environmental pressures, malnutrition, and socioeconomic wellbeing. We analysed key food system structure metrics that enable a nuanced understanding of multiple aspects of agricultural production in comparison to single metrics (e.g., 'agricultural value added per worker'). In terms of outcomes, for instance, we expressed malnutrition outcomes by prevalence of obesity and undernourishment, which are conclusive endpoints of population health and nutritional status. Our typology explicitly links coexistent changes in food systems structure and outcomes and, thus, can provide a complementary and timely diagnosis to other typologies drawn upon share of dietary energy (Fanzo et al., 2020), diversity of food supply (Bentham et al., 2020; IFPRI, 2015), and the literature of food systems transformations.

Our typology is one of 'requisite simplicity' (Stirzaker et al., 2010) — we have uncovered important longitudinal differences across the globe spanning multiple countries and contrasted these findings with paradigms of productivity (i.e., production output per unit of input) and of systems efficiency and sustainability (i.e., the social, environmental, and economic links to optimized productivity). In doing so we have followed geopolitical boundaries and so excluded potential within-country diversities. This might be considered a limitation of our approach as it masks meaningful heterogeneity in food systems. However, we argue that by focusing on key geopolitical units, our typology can be used to inform national policymaking and international governance to leverage change in food systems (Abson et al., 2017). Secondly, we quantify and report our results under a general umbrella of agricultural production. We do not consider the details of different food types or groups (e.g., distinct structure and social-ecological outcomes amongst crops, livestock, or horticultural systems) because: a) previous studies are already available for this level (Poore & Nemecek, 2018; Springmann, Clark, et al., 2018); and b) in this study, we want to provide a holistic, quantitative, and complementary diagnosis of global food systems diversity to the body of literature in food systems transformations. Thirdly, the sample metrics included in our model and its period of assessment between 1995 and 2015 are a result of limitations in the availability and quality of the datasets explored. Other relevant metrics to our research problem were either excluded from our study due to insufficient observations (e.g., pesticide use) or unavailable for a reasonably long time to allow a longitudinal analysis (e.g., food loss & waste). Broader methodological reflections are elaborated in the Appendix 4 (Methodological reflections to chapter 4).

Despite these limitations, we have identified ‘progress’ in many metrics of food systems across a vast number of countries globally in the past two decades. However, this notion of progress, narrowly defined in terms of higher agricultural output or improved cost-efficiency of production, was broadly independent from (or even counter to) the ability of global food systems to mitigate coexistent forms of malnutrition, pressures to planetary boundaries, or socioeconomic vulnerabilities. By quantifying the contrasts between development pathways across national food production and trade settings, we can track the empirical change of dynamic social-ecological interactions. These distinctions are valuable because they: a) show patterns of incoherence between expected food system provisions (i.e., goals and aspirations) and what they actually deliver more explicitly (Poore & Nemecek, 2018; Springmann, Wiebe, et al., 2018); and b) reveal multiple pathways for food system development, which highlights that the future is not deterministic.

4.6 Conclusion

Our analysis shows that under current trajectories of change, “business-as-usual” propositions or “incremental-adaptation” initiatives focusing on higher yields alone are not only insufficient to achieve consensual global goals (e.g., ending hunger or limiting global warming to 1.5°C - Pradhan et al., 2017) but they could even hamper the attainment of other goals indirectly (e.g., health system costs for reasonable prevention and treatment of diet-related non-communicable diseases - Development Initiatives, 2020). Our conceptual design and quantitative assessment further reveal a novel entry point for exploring the intertwined challenges of sustainable food systems, in particular for a better understanding of temporal dynamics. Given the long term trajectories revealed, a step change in strategies is likely needed to make progress that includes improved resilience of supply chains, sustainable agriculture (e.g., no-till and precision agriculture, reduced reliance on synthetic fertilizers) and educational, economic, and environmental policies towards more plant-based diets (Nyström et al., 2019; Poore & Nemecek, 2018; Springmann, Clark, et al., 2018).

Essentially, the interdependence across global food systems requires policies consistent with their empirical trajectories and tailored for different transformation archetypes. Acknowledging the synergies between malnutrition, environmental, and social issues is key for sustainable development of food systems, in alignment with heterogeneity at smaller scales (i.e., within-country diversities). Finally, more research is needed to uncover comprehensive ‘watchpoints’ where there are adequate data to quantify shifts in trajectories, in response to targeted efforts to meet Sustainable Development Goals, as they apply to food systems at global, national and regional scales.

4.7 Declarations

4.7.1 Conflict of interests

The authors have no relevant financial or non-financial interests to disclose. The funders of the study had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

4.7.2 Data and code availability

The authors declare that the data supporting all figures of this study are available within the paper and the Appendix 4. The data that support the findings of this study are available from: the Food and Agriculture Organization of the United Nations (available from http://www.fao.org/faostat/en/#data), World Development Indicators, from the World Bank (available from https://databank.worldbank.org/source/world-development-indicators), SDG Indicators database, from the United Nations (available from https://unstats.un.org/sdgs/indicators/database/), Climate Analysis Indicator Tool, from the World Resource Institute (available from https://www.climatewatchdata.org/ghg-emissions?sectors=512%2C514), the International Labour Organization (available from https://ilostat.ilo.org/data/), the International Fertilizer Association (available from https://www.ifastat.org/databases), and the United States Department of Agriculture (available from https://www.ers.usda.gov/data-products/international-agricultural-productivity/). Furthermore, the authors declare that the scripts supporting all figures and results of this study are described in the Appendix 4 (Supplementary Table 4.8) and accession codes will be deposited into a public repository before publication.

CHAPTER 5

SYSTEMIC FOOD RISKS: SYNCHRONISED DYNAMICS OF SHOCKS TO NATIONAL FOOD AVAILABILITY AND SUPPLY

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André Dornelles and Tom Oliver jointly designed, wrote, and reviewed the manuscript. André Dornelles conducted the formal analysis and verified the underlying data. Tom Oliver and Richard Nunes reviewed the final text and provided critical comments to the manuscript.

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5.1 ABSTRACT

Global food supply has become increasingly interconnected, but research on the emergent properties of activities from production to consumption is still sparse. In this study, we used a model to quantify networks of 151 countries and identify synchronised dynamics from 1961 to 2013 in terms of interannual fluctuations and shocks in dietary energy supply (in kcal/person/day) and food supply (in tonnes) of crops (e.g., cereals, fruits, vegetables) and livestock (e.g., meat, milk, and eggs). Two main analyses of synchronised dynamics were applied: a) a dissimilarity matrix and cluster algorithm approach to investigate shared patterns in the magnitude of interannual fluctuations across countries; and b) a chi-squared test of frequency of shocks in pairs of countries to investigate co-occurrence of shocks. A Mantel test was then used to explore potential links to geographic distances or distinct components of metrics (e.g., food production in food supply). We found that geographic distance partially explained synchronous interannual fluctuations of dietary energy supply and food supply of crops and livestock across the globe. Additionally, dietary energy supply and food supply exhibited correlated interannual fluctuations and co-occurrence of shocks, whilst trade played a role in the prevention of shocks to food supply (i.e., buffering effect). Our model provides an empirical description of dynamic and shared patterns of interannual fluctuations across increasingly interconnected global food networks, with implications for national strategies of food security.

5.2 Introduction

Including all food systems activities from food production to consumption, food supply chains have extended across multiple geopolitical boundaries at a globalised scale. The development of global food networks inherently connected previously distant environmental, social, and economic realities through trade (Davis et al., 2021; Nyström et al., 2019). It is estimated that international trade mediates roughly 20% of the food, water, and land resources consumed by humans, and the population of multiple countries are dependent on such continuous flows for their survival (Marchand et al., 2016; Tu et al., 2019). The emergence of shared cross-scale dynamics and the intertwined nature of social-ecological systems related to food (Reyers et al., 2018), thus, invite a new paradigm to investigate the joint proprieties responsible for shocks and disruptions in more complex food networks.

As food supply chains are increasingly interconnected globally, a growing appetite to understand their dynamic proprieties has emerged, focusing on: synchronised fluctuations, emergent patterns, shock-amplifying or shock-dampening implications (i.e., positive and negative feedback loops, respectively), shock propagations (i.e., dissemination of failures across multiple nodes of a network), buffering effects (e.g., alternative routes or modules that can prevent or reduce shocks), potential cascades (e.g., from production, to trade, to consumption; across different sectors), and/or unexpected sources of vulnerability (Farmer et al., 2019; Gilarranz et al., 2017; Homer-Dixon et al., 2015; Nyström et al., 2019; Tu et al., 2019). These innovative approaches have explored shock events to food beyond their impact on food production, and thus enable an expanded lens to assess the capacity to cope with potential future disruptions at multiple stages (Davis et al., 2021).

5.2.1 The nature of shocks to food availability and supply

A growing body of research has been investigating the susceptibility to food shocks, predominantly focused on four major crops (e.g., soy, maize, rice, and wheat – Mehrabi & Ramankutty, 2019) and other agricultural commodities (e.g., livestock, fisheries, palm oil, sugarcane). These reports are commonly measured in quantity (e.g., tonnes and yields) or monetary units (e.g. international dollars) in the production (e.g., farms – Cottrell et al., 2019) or in the distribution stages (e.g., trade networks – Distefano et al., 2018) of food systems, often in isolation (Davis et al., 2021). Particularly in the production stage, robust assessments accounting for multiple predictors have shown connections between stability of crop output (both in tonnes and in yields) and crop diversity (Renard & Tilman, 2019) and/or crop asynchrony (i.e., asynchronous production trends between different crops - Egli et al., 2020). Conversely, the dynamics of availability of food items (i.e., kcal/person/day or tonnes) have been assessed in the consumption stage (Bentham et al., 2020), specifically accounting for food-group combinations responsible for variations in food supply across countries. Finally, Tu *et al.* (2019) investigated the resilience and sustainability of global dynamics between the production stage and trade flows of food resources (e.g., land and water), with refined analytical features (e.g., connectivity, modularity, and heterogeneity). These approaches have helped to broaden the scope across different food systems stages where shocks might occur (i.e., between food production and consumption), and reveal the interdependent nature of the systemic dynamics responsible for the potential emergence of such shocks (e.g., synchronised fluctuations across networks or buffering capacity of some countries).

An analysis of emergent patterns in interannual fluctuations of dietary energy supply and food supply is relevant for a dynamic understanding of, for instance: a) the elements behind detected shocks, b) potential systemic risks emerging in elements which have not yet been translated into shocks, or c) shared patterns across different countries or groups of countries that might be more susceptible to an eventual shock. This paper aims to quantify networks of 151 countries and understand synchronised dynamics in terms of interannual fluctuations and shocks in dietary energy supply (in kcal/person/day) and food supply (in tonnes) of crops and livestock from 1961 to 2013. Patterns are explored by factors such as geographic distance (i.e., in kilometres) and distinct components of food supply (i.e., production, imports, and exports). From a systemic risk perspective, we show how this approach can reveal emergent and simultaneous shock patterns in dietary energy supply and food supply. Our model enables an investigation of changes over time in diverse food groups and multiple stages of the food system simultaneously (i.e., beyond consumption or production in isolation). Our study is thus relevant to empirically identify dynamic and shared patterns across increasingly interconnected global food networks and help to inform strategies for food security.

5.3 Methods

5.3.1 Overview

Our study mainly focused on the dynamics of dietary energy supply (in kcal/person/day) and of food supply (in tonnes) of crops and livestock from 1961 to 2013. The interannual fluctuations of dietary energy supply and food supply assessed in our study were reported in terms of magnitude and frequency. Magnitudes of interannual fluctuations were expressed as the change in raw values between the focal year and the year preceding it. Frequencies of extreme events (i.e., crashes, which we herein refer to as ‘shocks’, or rapid growth events) were reported as binary values: 0 representing the absence of an extreme event and 1 its presence (see ‘Data analysis’ section for thresholds).

We conducted two analyses of synchronised dynamics in dietary energy supply and food supply of crops and livestock: a) a dissimilarity matrix and cluster algorithm approach to investigate shared patterns in the magnitude of interannual fluctuations across countries; and b) a chi-squared test of frequency of shocks in pairs of countries to investigate co-occurrence of shocks. Results from both analyses were then put to a Mantel test to explore potential links to geographic distances or distinct components of metrics (e.g., food production as a part of food supply). More specific details are described in the 'Data analysis' section.

5.3.2 Data acquisition

We conducted a comprehensive search of publicly available repositories and official databases to acquire data on dietary energy supply and food supply (more details in the 'Data and code availability' section). We assessed emergent patterns in dietary energy supply and food supply specifically related to crops and livestock (and their nine food groups, described below under tier 3), instead of using data for all 18 food types and groups reported by FAO (2001). We did not include all food groups due to: a) potential difficulties and methodological inconsistencies to compare food groups across diverse stages of food systems as staple foods (e.g., in the case of 'sugar and sweeteners', 'animal fats', or 'vegetable oils') and/or b) low contribution to longitudinal fluctuations relevant to food security and the aim of this study (e.g., in the case of 'stimulants', 'offals', and 'aquatic products'). Crops and livestock composed the primary assessment lens of our study because: a) they represent the majority of dietary energy supply across countries (average of 71.9%, minimum of 46% and maximum of 96.2%, no. = 151 countries); b) their key importance for the food supply chain and methodological consistency which enables comparisons across different food systems stages, from production, to trade, to consumption; and c) the comprehensiveness of data availability across multiple countries for an extensive time period (from 1961 to 2013).

The two main metrics of analysis in our study were dietary energy supply and food supply. Dietary energy supply represents food directly available to human consumption (expressed as kcal/person/day), composed by production plus imports, plus changes in stocks (decrease or increase) minus exports (FAO, 2001). Food supply was expressed in tonnes, composed by food production plus imports minus exports. Food supply comprises total food-related commodities and thus also contains relevant information, for instance, before food losses or use for feed and seed. We used total food supply in tonnes instead of yields (i.e., output relative to area) because this offers additional insights into food security and because it enables simpler conversions to other metrics which might express different denominators (e.g., per capita or per hectare). Components of food supply were represented by food production (i.e., magnitude of crops and livestock agricultural output), exports (i.e., weight of crops and livestock traded to be consumed abroad), imports (i.e., quantity of crops and livestock flowing from other countries). Both dietary and energy supply were divided into different tiers: tier 1 (totals, crops plus livestock), tier 2 (crops and livestock, quantified separately), and tier 3 (aggregated by food groups: cereals, fruits, treenuts, pulses, starchy roots, and vegetables integrated food groups related to crops, whilst meat, milk, and eggs composed livestock). The different components and food groups of dietary energy supply and food supply are illustrated in Supplementary Figure 5.1 – Appendix 5.

Other metrics computed in this study were geographical distance between pairs of countries, prevalence of obesity, and prevalence of undernourishment. Geographical distance revealed the pair-wise distance between countries, expressed in kilometres. Points of reference for distance calculations were adjusted by latitudes, longitudes and from a centroid in each country weighted by population agglomerations (Mayer & Zignago, 2011). Prevalence of obesity was the percentage of adults (18+ years) whose Body Mass Index (BMI) was greater than or equal to 30. Undernourishment measured the share of the population with an insufficient caloric intake to meet the minimum energy requirements necessary for a given individual (FAO et al., 2020).

5.3.3 Data preparation

The metrics acquired were collated into a hierarchical (i.e., tier 1, tier 2, and tier 3) and standardized format by ‘country’, ‘year’, and ‘value’. Dietary energy supply and food supply followed categorization under embedded tiers: tier 1) corresponding to the total aggregation of kcal/person/day for dietary energy supply and of tonnes for food supply from crops and livestock combined; tier 2) relative quantity of crops and livestock separately; and tier 3) analysis of dietary energy supply for each food group separately (cereals, fruits, treenuts, pulses, starchy roots, and vegetables, meat, milk, and eggs; Supplementary Figure 5.1 – Appendix 5). The measurement of food supply comprised components of food production (i.e., magnitude of crops and livestock agricultural output), food imports (i.e., quantity of crops and livestock flowing from other countries), and food exports (i.e., weight of crops and livestock traded to be consumed abroad). In a similar way to the tiered analysis of dietary energy supply, we first analysed food supply as an aggregate category (total tonnes), then for each component of production, imports and exports separately, and, finally, for each food group. All components of food supply shared the same organisation under tiers described for dietary energy supply. Preparation of data under this scheme allowed for a comparable assessment of interannual fluctuations between dietary energy supply and food supply shared across countries, as well as it enabled a detailed analysis of emergent patterns in the metrics of interest driven by their distinct component(s) or food group(s).

The time period of our study was from 1961 to 2013. Although data for some of the metrics of interest were available after 2013, one of the main metrics of interest (dietary energy supply) had a substantial methodological update from 2014, which limited potential analysis from that point onwards. Longitudinal comparisons between the two time series would result in discrepancies, which would be particularly problematic for our aim to investigate interannual fluctuations in the long-term (FAO, 2014). A filter was used to determine the maximum number of countries with comparable durations (i.e., number of years) and periods (i.e., in a similar time period) for each metric, covering at least 90% of the 53-year window (Supplementary Figure 5.2 and Supplementary Table 5.1 – Appendix 5). We considered two promising time periods (1961-2013 and 1990-2013) to explore the trade-off between covering more countries but over fewer years, but we report our findings for the period from 1961 to 2013 here due to higher number of observations. The filter resulted in 151 countries from 1961 to 2013 or 170 countries from 1990 to 2013 for dietary energy supply, whilst the food supply comprised 171 countries from 1961 to 2013 or 194 from 1990 to 2013.

5.3.4 Data analysis

Data analysis in our study was conducted from two perspectives, with two steps each (i.e., a first step of interannual changes and a second step of synchronised dynamics). The first perspective was an analysis of magnitude of interannual fluctuations, producing a dissimilarity matrix to compare patterns across countries and using a cluster algorithm to identify groups with shared dynamics. The second perspective was an analysis of frequency of extreme events, including a chi-squared test to assess synchrony between pairs of countries. Both perspectives of magnitude and frequency were then investigated for potential links to geographic distance or distinct food supply components (e.g., food production).

5.3.4.a Interannual changes

Interannual fluctuations were calculated by the subtraction of the raw value of the focal year by its lag value, representing the magnitude of interannual change of dietary energy supply and food supply of crops and livestock. The identification of extreme events (i.e., shocks and growths) was developed from this analysis of interannual fluctuations. Shocks and growth events to dietary energy supply and food supply were identified as years in which the magnitude of the interannual fluctuation was greater than two times the median absolute deviation (i.e., > ± 2MAD). This criterion was used to identify extreme events relative to deviation measures in 11-year moving windows (by running MAD in each moving window, covering 5 years on either side of the focal year). Because of the mathematical relationship between median and variance, using a moving time window is more appropriate when timeseries show a non-stationary median; and so extreme events are defined relative to the local variance. In the case of food exports, shocks and growths were calculated in the opposite direction to other metrics because they are inversely related to food supply. In other words, if food exports spiked, for instance, it negatively impacted the food supply for that country.

5.3.4.b Synchronised dynamics

We conducted two main analyses of synchronised dynamics for dietary energy supply and food supply of crops and livestock: a) a dissimilarity matrix based on magnitude of interannual fluctuations between countries followed by cluster algorithm and b) a chi-squared test to assess co-occurrence of extreme shocks between pairs of countries. In both cases, these were followed by a Mantel test to investigate potential links with geographic distances between countries. Additionally, we explored potential buffering events in individual components of food supply (i.e., food production, imports, and exports). Buffering events were defined in this study as years in which shocks to components of food supply were not translated to a shock in the aggregated metric. Mainly, we focused our analysis of buffering events on the shocks to food production which were not translated to shocks in food supply, because: a) out of the three components of food supply, food production represents its biggest share, and b) interannual fluctuations of food supply and food production are closely correlated (Table 5.1).

The dissimilarity matrix was used to investigate shared patterns in the magnitude of interannual fluctuations across countries and the cluster algorithm was applied to identify the most parsimonious groups of countries. Firstly, a correlation matrix was created using Pearson's correlation coefficient for the interannual fluctuations in dietary energy supply and food supply for each pair of countries. Pearson’s correlation coefficients in this initial matrix varied from -1 (indicating perfect inverse correlation) to +1 (revealing perfect direct correlation). To enable the application of the cluster algorithm, all values in the matrix needed to be recorded as Euclidean distances and so, to that end, the correlation coefficients were multiplied by -1 and then increased by +1, thus creating a dissimilarity matrix ranging from 0 (showing perfect positively correlated interannual dynamics) to +2 (expressing perfect negative correlation). These synchrony scores (i.e., synchronous interannual fluctuations) were also used for the Mantel test analysis, subsequently to the cluster algorithm.

For the second step in the analysis, a hierarchical cluster algorithm was applied to the dissimilarity matrix (transformed from the correlation matrix). We used the R package *NbClust* (Charrad et al., 2014) which runs multiple clustering indices simultaneously, in addition to testing different combinations of distance measures and aggregation methods. Due to the format of the matrix investigated (i.e., dissimilarity matrix), five indexes were appropriate for use: Silhouette (based on the maximum value of the index), Frey (based on the cluster level before that of index value < 1.00), McClain (based on the minimum value of the index), Cindex (based on the minimum value of the index), and Dunn (based on the maximum value of the index). The final output from these five clustering indexes indicated the most parsimonious clustering scheme across all countries (in terms of number of groups and their respective composition). To test for statistical differences in dietary energy supply, food supply, undernourishment, and obesity across clusters, an analysis of variance model was used (after the implementation of the Shapiro-Wilk test of normality). Tukey's honest significance test was applied to scrutinize differences between specific groups. Statistical significance threshold was set at 0.05.

To investigate the frequency of co-occurrence of individual shock events to dietary energy supply and food supply of crops and livestock across countries, we applied a chi-squared test to all pairs of countries. The frequency of shocks in each country was identified by the binary values 1 (shock; a crash in the metric defined by a threshold of 2MAD, see above) and 0 (absence of shock) at an annual level. As the first step to investigate co-occurrence of shocks between countries in the same year (s), unique pairs of countries and respective contingency tables were computed for dietary energy supply and food supply. A chi-squared test was applied to the contingency table of frequency of shocks for each iteration between the specified country A and country B, and this was repeated for all unique pairs of countries. The four potential outcomes from the contingency table for each pair was: 1) absence of shock in both countries; 2) absence of shock in country A with shock occurring in country B; 3) shock occurring in country A with lack of shock in country B; 4) shocks occurring in both countries. The chi-squared test was used to determine whether the observed frequencies of each of the four outcomes were higher than their expected frequencies. In the case of a significantly higher observed probability in comparison to expected probability for outcomes 1 or 4, it was concluded that synchrony of shock events occurred (i.e., co-occurrence of shocks). If a significantly higher probability than expected by chance arose for outcomes 2 or 3, asynchrony of shock events was assumed for the pair of countries (i.e., inversely correlated shock events). Under alternative probabilistic scenarios, no clear pattern of synchrony or asynchrony was assumed.

To investigate the potential links between co-occurrence of shocks, synchronous interannual fluctuations, and geographic distances or distinct components of metrics (e.g., food production in food supply), a Mantel test was applied as the final step in both analyses of magnitude and frequency. Separate Mantel tests explored the correlation between geographic distances and the two matrices of interest: dissimilarity matrices (from the perspective of magnitude) and chi-squared matrices (for frequency of shocks). Dissimilarity matrices of dietary energy supply, food supply, and its components contained the adjusted Pearson's correlations scores of interannual fluctuations. The matrices of co-occurrence of shocks were composed of p-values from their respective chi-squared tests. The matrix of geographic distance was composed of inter-country distances in kilometres (see above for population weighted-centroids). P-values from the Mantel test were then determined by comparing the sum of the distance values between the two matrices to the sums of randomized permutations of the matrices. P-values were calculated by dividing the number of times that the sum of the matrices was higher than the original nonrandomized matrices by the number of permutations plus the number of times the sum was higher (Mantel, 1967).

5.4 Results

5.4.1 Overall trends in food supply networks

From 1961 to 2013, dietary energy supply and food supply of crops and livestock have grown, following an upward trend across decades. Dietary energy supply increased from a global average of 1,691.4 (± 316 SD) kcal/person/day between 1961-1965 to 1,944 (± 280 SD) kcal/person/day between 2009-2013. Food supply, measured in absolute weight, grew substantially within the same period: from an average of 1.3 x 10^7 tonnes between 1961-1965 to 4.3 x 10^7 tonnes between 2009-2013 (an absolute growth of more the three times the baseline values globally). We found a similar pattern in terms of interannual fluctuations (i.e., delta between years) of dietary energy supply (from a positive delta of 6.9 kcal/person/day between 1961-1965 to 9.3 kcal/person/day between 2009-2013) and food supply (from a growing difference of 2.1 x 10^5 tonnes between 1961-1965 to 1.1 x 10^6 tonnes between 2009-2013). Pair-wise correlations between the metrics of interest ranged from close to zero to weak, with exception of the correlation between food supply and food production, which was strong (i.e., Pearson's correlation score of 0.97) – Table 5.1.

Table 5.1 – Pair-wise correlations between interannual fluctuations of dietary energy supply, food supply of crops and livestock, and its components (i.e., production, imports, and exports) from 1961 to 2013.

	Dietary energy supply	Food supply	Food production	Food exports	Food imports
Dietary energy supply	1	0.09	0.08	0.05	-0.01
Food supply		1	0.97	0.22	-0.25
Food production			1	0.09	-0.03
Food exports				1	-0.11
Food imports					1

Values reported express the Pearson’s correlations scores between interannual fluctuations of each metric.

We found 1,622 extreme interannual changes (20.2% of all possible events) in dietary energy supply of crops and livestock across 151 countries between 1961 to 2013, with 811 shock events (10.1%) and 811 growth events (10.1%) – revealing a reasonably steady pattern of shocks and growth events across decades (Figure 5.1, A). Food supply displayed a similar trend of extreme events across 171 countries in the same period (1,892 events, 20.8% of all observations), with 874 shocks (9.6%) and 1,081 growth events (11.2%) – Figure 5.1, B. Extreme events to distinct components of food supply suggested more volatility, in particular for trade components: food production – 1,948 extreme events (21.5% of all cases), 957 shock events (10.6%), and 991 growth events (10.9%); food imports – 2,196 extreme events (24.2% of all possible events), 1,053 shock (11.6%), and 1,143 growth events (12.6%); and food exports – 3,381 extreme events (37.2% of all observations), 1,717 shocks (18.9%), and 1,664 growths (18.3%). The frequency of shocks to both dietary energy supply and food supply of crops and livestock tended to be quite balanced globally, with a slightly predominant concentration of shocks to food supply found in South America and Sub-Saharan Africa (Figure 2).

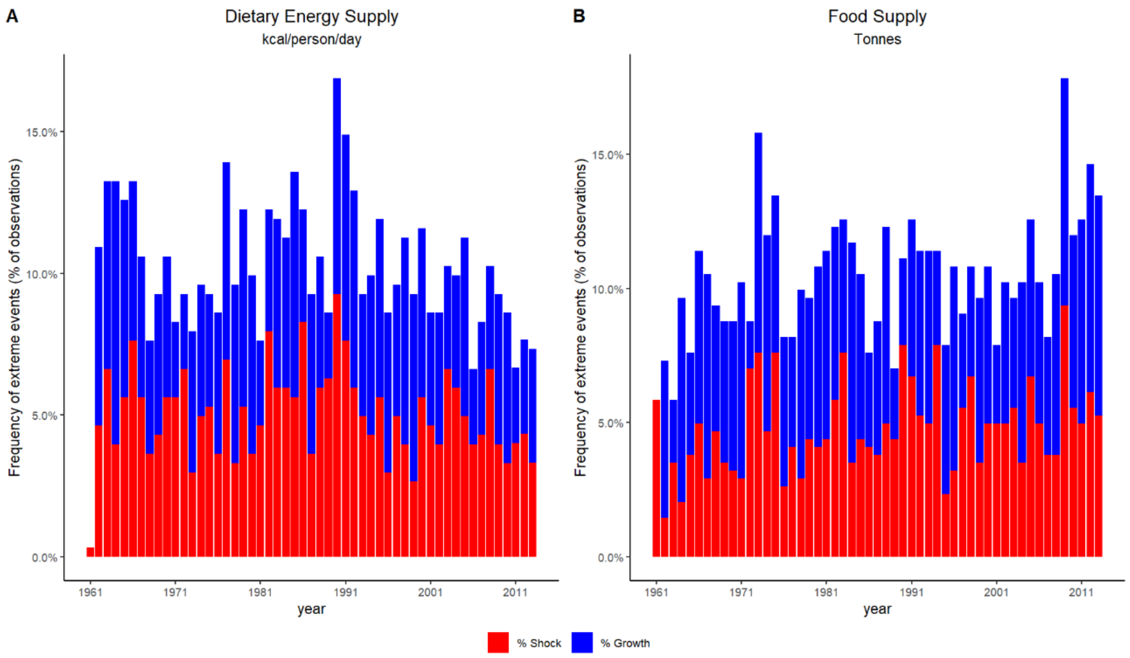


Figure 5.1 – Frequency of extreme events across the globe from 1961 to 2013 for dietary energy supply (A) and food supply (B) of crops and livestock. Extreme events are determined by years in which interannual fluctuations are > ±2MAD (median absolute deviation) relative to moving 11-year windows (i.e., covering 5 years on either side of the focal year).

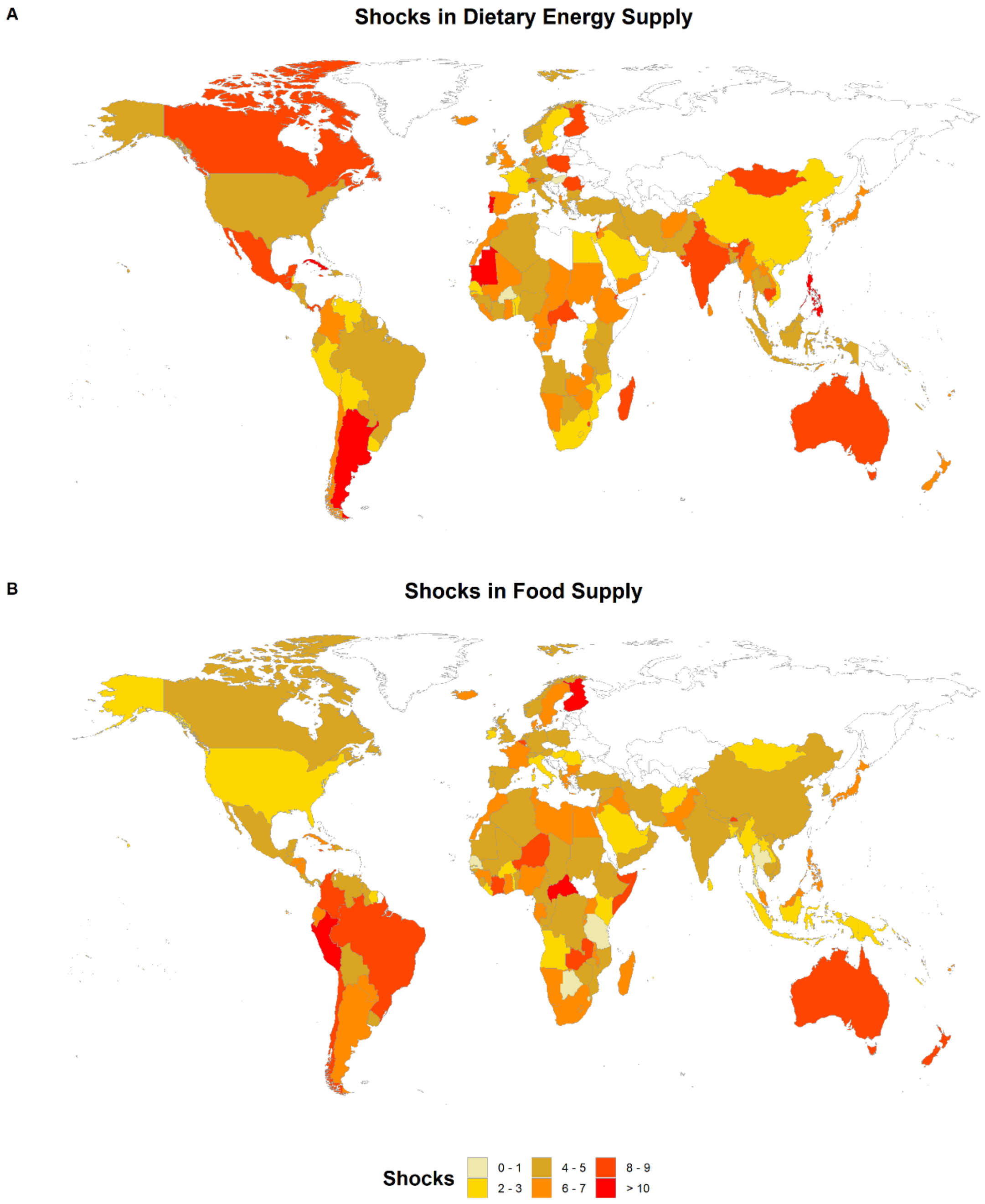
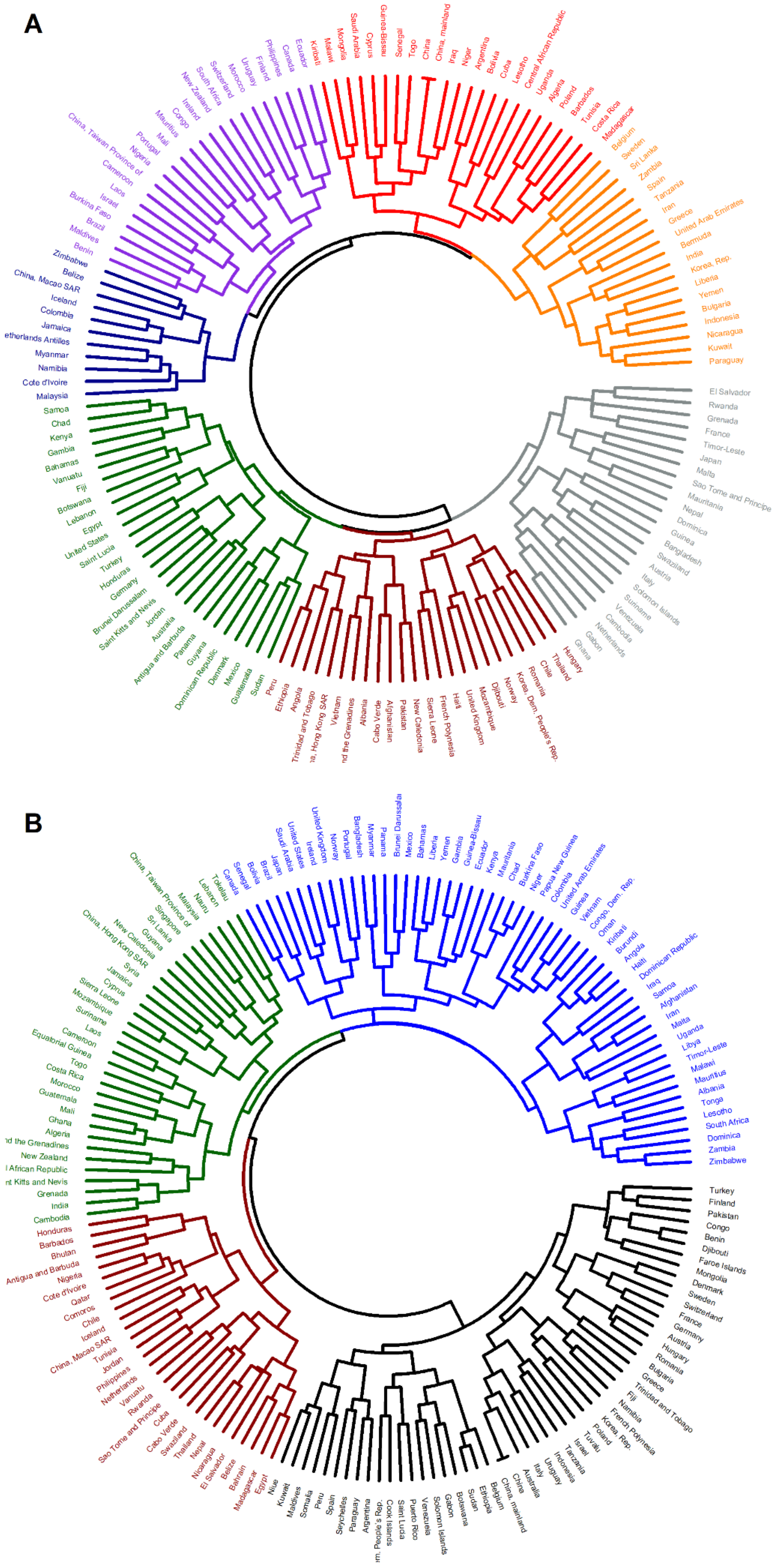


Figure 5.2 – Frequency of shocks in dietary energy supply (A) and food supply (B) of crops and livestock across countries from 1961 to 2013. Shocks are defined as interannual declines >2MAD (median absolute deviation) within an 11-year moving window.

5.4.2 Synchrony in the magnitude of interannual fluctuations

We found low to mildly informative clustering schemes from our analysis of dissimilarity matrix and cluster algorithm applied to interannual fluctuations of dietary energy supply and food supply of crops and livestock. For dietary energy supply, the five indexes modestly supported the categorisation of interannual fluctuations across 151 countries into seven clusters, with this clustering scheme ranking amongst the most appropriate indexes performances (Silhouette: 0.0364; Frey: 0.0838; McClain: 4.8917; Cindex: 0.6724; and Dunn: 0.4063; Figure 5.4, panel A). Under these seven clusters, some weak differences were identified amongst groups for absolute kcal/person/day, particularly important in group 3 (n = 27 countries), which showed generally higher rates of obesity and lower prevalence of undernourishment despite a lower availability of dietary energy supply (Supplementary Figure 5.3 – Appendix 5). There were no clear distinctions for the total magnitude of interannual fluctuations (i.e., delta between years) across groups. The dissimilarity matrices of dietary energy supply indicated 153 pairs of countries (out of 11,325 unique pairs across all 151 countries) with synchronous interannual fluctuations (i.e., synchrony values ≤ 0.5).

For the interannual fluctuations of food supply, four clusters were more robustly supported by the five indexes across 171 countries (Silhouette: 0.0527; Frey: 1.5779; McClain: 2.633; Cindex: 0.6122; and Dunn: 0.3037; Figure 5.4, Panel B). These four clusters revealed consistent differences; for example, group 4 (n = 53 countries) showed higher absolute and interannual fluctuations of food supply weight, followed by lower prevalence of undernourishment and higher proportion of obesity (Supplementary Figure 5.4 – Appendix 5). On the other hand, group 3 (n = 29 countries) tended to show both the lowest availability of food supply and the higher prevalence of undernourishment. Finally, dissimilarity matrices of food supply indicated 299 pairs of countries (out of 14,535 unique pairs across all 171 countries) with synchronous interannual fluctuations.


A
Philippines
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Malawi
Mongolia
Saudi Arabia
Cyprus
Guinea-Bissau
Senegal
Togo
China
China, mainland
Iraq
Niger
Argentina
Bolivia
Cuba
Lesotho
Central African Republic
Uganda
Algeria
Poland
Barbados
Tunisia
Costa Rica
Madagascar
Belgium
Sweden
Sri Lanka
Zambia
Spain
Tanzania
Iran
Greece
United Arab Emirates
Bermuda
India
Korea, Rep.
Liberia
Yemen
Bulgaria
Indonesia
Nicaragua
Kuwait
Paraguay
El Salvador
Rwanda
Grenada
France
Timor-Leste
Japan
Malta
Sao Tome and Principe
Mauritania
Nepal
Dominica
Guinea
Bangladesh
Swaziland
Austria
Italy
Solomon Islands
Suriname
Venezuela
Cambodia
Netherlands
Ghana
Gabon
Hungary
Thailand
Chile
Romania
Korea, Dem. People's Rep.
Norway
Djibouti
Mozambique
United Kingdom
Haiti
French Polynesia
Sierra Leone
New Caledonia
Pakistan
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a, Hong Kong SAR
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Peru
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Denmark
Dominican Republic
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Australia
Jordan
Saint Kitts and Nevis
Brunei Darussalam
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Honduras
Turkey
Saint Lucia
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Bahamas
Gambia
Kenya
Chad
Samoa
Malaysia
Cote d'Ivoire
Namibia
Myanmar
etherlands Antilles
Jamaica
Colombia
Iceland
China, Macao SAR
Belize
Zimbabwe
Benin
Maldives
Brazil
Burkina Faso
Israel
Laos
Cameroon
China, Taiwan Province of
Nigeria
Portugal
Mali
Mauritius
Congo
Ireland
New Zealand
South Africa
Switzerland
Morocco
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Malaysia
Lebanon
Nauru
Tokelau
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Senegal
Bolivia
Brazil
Japan
Saudi Arabia
United States
Ireland
United Kingdom
Norway
Portugal
Bangladesh
Myanmar
Panama
Brunei Darussalam
Mexico
Bahamas
Liberia
Yemen
Gambia
Guinea-Bissau
Ecuador
Kenya
Mauritania
Chad
Burkina Faso
Niger
Papua New Guinea
Colombia
United Arab Emirates
Guinea
Vietnam
Congo, Dem. Rep.
Oman
Kiribati
Burundi
Angola
Haiti
Dominican Republic
Iraq
Samoa
Afghanistan
Iran
Malta
Uganda
Libya
Timor-Leste
Malawi
Mauritius
Albania
Tonga
Lesotho
South Africa
Dominica
Zambia
Zimbabwe
Turkey
Finland
Pakistan
Congo
Benin
Djibouti
Faroe Islands
Mongolia
Denmark
Sweden
Switzerland
France
Germany
Austria
Hungary
Romania
Bulgaria
Greece
Trinidad and Tobago
Fiji
Namibia
French Polynesia
Korea, Rep.
Poland
Israel
Tuvalu
Tanzania
Indonesia
Uruguay
Italy
Australia
China
China, mainland
Belgium
Ethiopia
Sudan
Botswana
Gabon
Solomon Islands
Venezuela
Puerto Rico
Saint Lucia
Cook Islands
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Seychelles
Spain
Peru
Somalia
Maldives
Kuwait
Niue
Egypt
Madagascar
Bahrain
Belize
El Salvador
Nicaragua
Nepal
Thailand
Swaziland
Cabo Verde
Cuba
Sao Tome and Principe
Rwanda
Vanuatu
Netherlands
Philippines
Jordan
Tunisia
China, Macao SAR
Iceland
Chile
Comoros
Qatar
Cote d'Ivoire
Nigeria
Antigua and Barbuda
Bhutan
Barbados
Honduras
Cambodia
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l African Republic
New Zealand
nd the Grenadines
Algeria
Ghana
Mali
Guatemala
Morocco
Costa Rica
Togo
Equatorial Guinea
Cameroon
Laos
Suriname
Mozambique
Sierra Leone
Cyprus
Jamaica
Syria
China, Hong Kong SAR
New Caledonia
Guyana
Sri Lanka
Singapore

Figure 5.3 (continued from previous page) – Circular dendrogram of interannual fluctuations to dietary energy supply (A) and food supply (B) of crops and livestock across countries from 1961 to 2013. Each edge represents a country, and each coloured branch represents a cluster sharing similar interannual dynamics.

5.4.3 Co-occurrence of discrete shock events

Our chi-squared test of co-occurrence of shocks found some synchronous patterns of shocks between countries, but no significant associations were found for asynchrony of shocks between countries. Myanmar and Luxembourg were excluded from the chi-squared test for dietary energy supply of crops and livestock due to absence of shock events from 1961 to 2013, whilst Senegal were excluded from the food supply analysis for the same reason. Synchronous co-occurrences of shocks were found in 231 pairs of countries for dietary energy supply (out of 11,026 unique pairs across all 149 countries) and in 306 pairs of countries for food supply (out of 14,365 unique pairs across all 170 countries). Shocks to dietary energy supply were modestly linked to shocks in food supply across the 148 countries both in terms of co-occurrence of shocks (Mantel r = 0.018; p-value = 0.04) and of synchronous interannual fluctuations (Mantel r = 0.1; p-value < 0.01). Finally, synchronous interannual fluctuations and co-occurrence of shocks in food supply and food production of crops and livestock were strongly correlated (Mantel r = 0.5553 and 0.1273, respectively; p-value < 0.01).

5.4.4 Association of synchronised dynamics with geographic distance

Mantel tests investigated synchronised dynamics in dietary energy supply and food supply of crops and livestock both in terms of frequency (i.e., co-occurrence of shocks) and magnitude (i.e., synchronous interannual fluctuations). Geographic distance was moderately associated with synchronous interannual fluctuations of dietary energy supply (Mantel r = 0.029; p-value < 0.01) and food supply (Mantel r = 0.058; p-value <

0.01) of crops and livestock across countries, but no clear link was found in terms of co-occurrence of shocks in either metric (p-values of 0.13 and 0.2, respectively). The dissimilarity matrices of dietary energy supply indicated 153 pairs of countries with synchronous interannual fluctuations (i.e., synchrony values ≤ 0.5), whilst 299 pairs of countries were identified for food supply.

5.4.5 Buffering to shocks to food supply mediated by trade

In our analysis of buffering effects to food supply, we found that from the 874 shocks to food supply of crops and livestock from 1961 to 2013, 397 of those were not co-existent with a shock in food production (45.4%), despite the high correlation between these metrics in terms of interannual fluctuations. Out of the 954 shocks found in production in the period analysed, 477 of these were not translated to shocks in food supply (i.e., indicating a potential buffering effect from trade). In these cases, approximately half of the buffering events were found in years in which there were either: a) growth spikes in imports (n = 109, 22.8% of buffering events, with average import increases more than eight times bigger than overall interannual trends), b) extreme reductions in exports (n=108, 22.5%, with average interannual reductions almost five times more severe than general fluctuations), and/or c) a combination of *a.* and *b.* (n=29, 6%, with similar import values to *a.*, but three times steeper reductions in exports relative to *b.*). In the remaining occasions, no perceived extreme events (i.e., spikes or crashes) were identified in food imports or exports, but their interannual fluctuations tended to be twice the overall trends for increase in imports and for reduction in exports.

In summary, these 477 shock events to food production appear to be buffered by trade, thus playing a role in the prevention of shocks to food supply. Thirty-one countries experienced 192 (~40%) of these production buffering events, showing five or more events between 1961 and 2013. These countries tended to be below the 50th percentile of total shock events to food supply (in terms of total number of shocks), suggesting a protective effect of such buffering events. In Figure 5.4 we report interannual fluctuations of food supply, production, import and export, for two countries as case studies to illustrate such phenomena: (A) Ireland in which shocks to production were 'buffered' by trade, and (B) Uganda in which they were not.

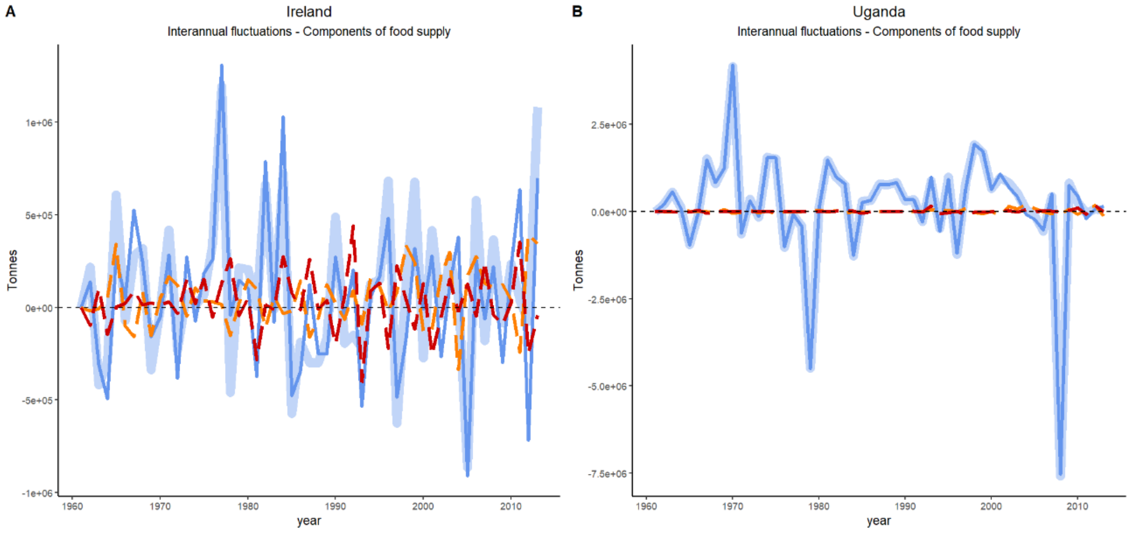

Figure 5.4 – Case studies of buffering events to food supply: (A) Ireland in which shocks to production were 'buffered' by trade and (B) Uganda in which they were not. Buffering events identified here describe shock events to food production which were buffered by trade (i.e., imports and exports) and thus played a role in the prevention of shocks to food supply. Colouring scheme: food supply – wider light blue solid lines; food production – darker blue solid lines; food imports – dark orange dashed lines; food exports – dark red dashed lines.

5.5 Discussion

In this study, we quantified synchronised dynamics in terms of interannual fluctuations and shocks in dietary energy supply and food supply of crops and livestock from 1961 to 2013 across more than 150 countries. In terms of explaining shared dynamics, we found that geographic distance partially explained synchronous interannual fluctuations of dietary energy supply and food supply across the globe, though not the co-occurrence of shocks. We also found that a capacity to rapidly modify imports and exports led to the buffering of extreme shocks, which can explain why some countries suffer food supply issues whilst others do not.

The clustering analysis indicated that the interannual fluctuations of dietary energy supply and food supply do not clearly link to traditional indicators of food security (e.g., availability of food or prevalence of malnutrition). However, it does quantify the extent and timing of fluctuations (i.e., synchrony in a yearly basis) across countries and a new way of characterising emerging systemic risks to the global food system.

5.5.1 Systemic food risks

The interdependence of multiple elements within global food networks requires an expanded notion of susceptibility to shocks and increased volatility beyond the production stage (Davis et al., 2021; Hamilton et al., 2020). Previous studies have tended, however, to focus on the production of crops more specifically, and their relative global instability, local instability, and synchrony within and between maize, rice, soybean and wheat (Egli et al., 2020; Mehrabi & Ramankutty, 2019; Renard & Tilman, 2019). Cottrell *et al.* (2019) comprehensively qualified drivers of shocks (e.g., weather events and geopolitical crises) to the production of crops, livestock, fisheries, and aquaculture. Complementarily to Cottrell *et al.* (2019), who have analysed coexistent shocks within nations (and their different food sectors), we have quantified the co-occurrence of shocks across multiple territorial and temporal scales and throughout the supply chain (i.e., between production and supply). Our assessment of the emergence of synchronised dynamics within multiple components of the supply chain, in this sense, can be a valuable first step to anticipate losses or to link latent propagations of shocks from the production to consumption stages shared across countries.

Increased connectivity and decreased diversity of global food supply reveal important characteristics relevant for systemic food risks mediated by international trade (Hamilton et al., 2020). We reported the buffering effects of trade between food production and food supply, which has been corroborated particularly in developed and high-income countries (Distefano et al., 2018). From a network perspective of resilience, the increased connectivity (i.e., links and nodes) of global food supply needs further exploration concerning the positive and negative role of heterogeneity (i.e., correlation between the number of imports and exports links every node has) and modularity (i.e., the extent of interactions between subsystems and within-a-subsystem - Tu et al., 2019). More specifically, a tendency of trade dependency (i.e., imports of substantial quantities of food beyond own levels of production and/or exports) displayed by countries can simultaneously increase local food supply stability and erode the long-term resilience of global food systems under current structures (Nyström et al., 2019; Tu et al., 2019). Our study invites new questions about trade dependency and the diversification of imports for systemic risks: are foods being sourced from diverse countries or from diverse clusters of countries (i.e., groups of countries which do not show synchronous interannual fluctuations of food supply)? The implications for local and systemic risks can vary substantially if exporting countries compose similar nodes (i.e., sharing similar interannual fluctuations in food supply) and/or if they share analogous drivers to shocks (e.g., weather events and geopolitical crises).

Although we provide a conceptual and methodological advancement to the field of systemic food risks in this study, there were some limitations to be mentioned. We reported our findings as national values of dietary energy supply and components of food supply, which can mask relevant within-country heterogeneities. The comparison of data at an annual level also restrains interpretations at a finer temporal resolution (e.g., production shocks between seasons or months). More bottom-up approaches with a similar conceptual design to the one used in our study could be beneficial to understand the potential dynamic interactions of food security in the individual or at the household level, with variables, for instance, of accessibility to markets, volatility on food prices, and interactions with food environments (Nicholson et al., 2019). Additionally, our approach can arguably provide more meaningful information if data on international trade was expressed in terms of bilateral trade flows (i.e., with granular details, for instance, on countries of origin of imports and countries of destination for exports, with their respective quantities). Although some open-source datasets on bilateral trade flows of food exist (FAO, 2020), they tend to show inconsistencies which would be particularly limiting for our research design (e.g., declarations between importers and exporters differ, causing erroneous aggregated values). We were not able to access more reliable sources of bilateral trade flows at this stage of the study (Aguiar et al., 2019) due to economic restrictions for access. Finally, our results of food supply were reported in tonnes and not in monetary values (e.g., international dollars), which have been shown to be weakly correlated in the past in terms of shock propagations internationally (Distefano et al., 2018). A subsequent analysis of food prices under a similar study design of synchronous dynamics could provide additional insights on the absorption of shocks across different countries or clusters of countries based on income or level of development.

5.6 Conclusion

The increasing interconnectivity of global supply chains have raised important questions about systemic risk (Cottrell et al., 2019; Nyström et al., 2019). Here, we empirically identified dynamic and shared patterns of interannual fluctuations and shocks to dietary energy supply and food supply of crops and livestock globally. The capacity to forecast and adapt to shocks is not exclusive to one stage of the food systems, but inherent to the links between food production and consumption (Davis et al., 2021). Our research design, in this sense, is a relevant starting point to potentially inform sensitive intervention points in food systems (i.e., intervention kicks or shifts to underlying system dynamics in which the initial change is amplified by feedback effects and thus can magnify the impact of an intervention - Farmer et al., 2019).

Our analysis has shown that geographic distance and buffering by trade were able to partly explain synchronous interannual fluctuations of dietary energy supply and food supply across nations. In light of this, we found that countries fall into around seven clusters for dietary energy supply and four clusters for food supply of crops and livestock that share similar dynamics within these groups (i.e., they experience simultaneous interannual fluctuations). Currently, advice on diversification of supply chains to ensure national food security is often at the general level of "*don't put all your eggs in one basket*". However, diversifying supply has substantial overhead costs, so trade-offs with short term economic considerations need to also be managed. Our empirical approach may be valuable to help target diversification, e.g., importing food from countries in different clusters would suggest more resilient strategy than importing from multiple countries within the same cluster.

5.7 Declarations

5.7.1 Conflict of interests

The authors have no relevant financial or non-financial interests to disclose. The funders of the study had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

5.7.2 Data and code availability

The authors declare that the data supporting all figures of this study are available within the paper and the Appendix 4. The data that support the findings of this study are available from: the Food and Agriculture Organization of the United Nations (available from http://www.fao.org/faostat/en/#data), the SDG Indicators database, from the United Nations (available from https://unstats.un.org/sdgs/indicators/database/), and the GeoDist database (http://www.cepii.fr/CEPII/en/bdd_modele/presentation.asp?id=6), accessed in January of 2021. Furthermore, the authors declare that the scripts supporting all figures and results of this study will be deposited into a public repository before publication.

CHAPTER 6

“*The path toward sustainable food security and nutrition is often riddled with inaccurate and oversimplified beliefs regarding the requirements and impacts of such a strategy*” Shenggen Fan & Joanna Brzeska (2016)

SUMMARY & REFLECTIONS

In the introduction of this thesis, I developed a review of the literature about the conceptual foundations of food systems from an interdisciplinary perspective and proposed a conceptual framework to navigate food systems resilience and sustainability. In addition, the relevance for research and practice in linking the concepts of sustainability, resilience, and transformations in food systems culminated with the general aim of this thesis: investigating different mechanisms that ‘lock-in’ food systems into unsustainable pathways and evaluating how these mechanisms vary across countries. In manuscript 1, I conducted an academic literature analysis of different concepts related to ‘lock-in’ mechanisms across scientific disciplines and examined the potential of a bridging concept to understand this phenomenon integratively. It was found that lock-in mechanisms reveal an integrative understanding of social-ecological system dynamics responsible for persistent undesirable outcomes. As a co-author in manuscript 2, I actively participated in the design, writing, review, and edition of a study aiming to operationalise a comprehensive understanding between the undesirable properties of resilience (lock-ins) and their impacts on transformations towards sustainability in four case studies: pollinator decline, negative emissions technologies, plastic pollution, and increasing meat demand for human consumption. We found that enabling conditions (i.e., sharing common elements with multiple lock-ins) can provide meaningful insights to real world challenges, which help to unlock persistent and undesirable outcomes for societies and the environment.

In manuscript 3, I developed a data-driven approach aiming to identify ‘transformation archetypes’ in national food production and supply settings across the globe by exploring historical trends of input, output, productivity, and economic metrics and their social and environmental outcomes, involving 161 countries from 1995 to 2015. Global food systems transformation archetypes tended to be expanding in agricultural output, accompanied by persistent malnutrition and environmental pressures, independently of improvements to productivity (i.e., ratio of output to input). Finally, manuscript 4 investigated networks of 151 countries in terms of synchronised dynamics of emergent and simultaneous shock patterns in dietary energy supply and food supply from 1961 to 2013. Geographic distance partially explained synchronous interannual fluctuations in these metrics, whilst trade played a role in the prevention of shocks to food supply (i.e., buffering effect). Further details on the background, aim, hypothesis, methods, results, and discussions are found in each manuscript’s chapter.

6.1 Theoretical and practical reflections

6.1.1 Value added to the field

Each manuscript contributed to the field of sustainable and resilient food systems in particular ways, described below:

- Manuscript 1: this work provided vital insights to the growing use of the term resilience, often viewed normatively and used in silos across disciplinary boundaries. It is suggested that drawing a distinction between resilience and its overlooked flipside, undesirable resilience, can be beneficial for a coherent interdisciplinary use. The term ‘lock-in’ can act as a bridging concept to describe quantitative and qualitative constraint mechanisms, relevant for the understanding of social-ecological systems dynamics.
- Manuscript 2: building from the concept of ‘lock-in mechanisms’ elaborated in manuscript 1, this work introduced a solution-oriented approach and navigated potential pathways of transformations in the format of a perspective piece (i.e., by synthesis of literature from multiple sources elaborated under distinct case studies). This approach invites collaboration from multiple disciplines and allows a practical understanding of lock-in mechanisms: “what can we do about them”?
- Manuscript 3: more explicitly addressing the topic of food systems, this work engaged with an integrative research design (i.e., across multiple stages and dimensions of food systems) which provided a complementary diagnosis from a perspective of transformation of national food production and supply across the globe. This study highlights the need to consider food systems capable of delivering equitable benefits to both productivity and to human and environmental health.

- Manuscript 4: this study expanded the assessment of systemic food risks in terms of intertwined dynamics that reveal simultaneous shocks (i.e., synchronous interannual fluctuations across nations) between food production and availability within a reproducible model. This approach provides insights to the literature of systemic food risk and show implications for national strategies of food security, as it can, for instance, inform targeted diversification between food production and trade.

6.1.2 Personal reflections

As a collection of manuscripts, I would argue that their value added is represented by more than the mere sum of their individual parts. They might not have fundamentally changed the field at this stage of my career, as previously dreamed in my commonly naïve expectations in the pursuit of interdisciplinarity. Unsurprisingly to the eyes of more than a few reviewers that have assessed my submissions in the past, one of the most practical added values of my PhD journey was an improvement of my skills and metacognitive competence which predominantly enabled a recognition of my own limitations (Kruger & Dunning, 1999). My individual manuscripts, in this sense, represent a cycle. They have inherently changed me and hopefully some of the collaborators that I was able to engage in these 4 years of my PhD in the endeavours for the sustainable development of food systems. I was not able to propose solutions or interventions as answers to supposedly solve the very own problem of this thesis (i.e., lock-in mechanisms in global food systems) in a concrete manner. Nonetheless, I have improved my capacity to raise and address tangible questions with more refined designs and commensurable methods to continue to add value to the field of sustainable food systems in the upcoming years.

6.1.3 Future perspectives

In the short-term, I plan to develop the premises and skills I was able to advance during my PhD by: a) continuing with some of the ongoing research led by me (e.g., investigating the stability of dietary energy supply and food supply with links to synchronous patterns between food groups and, alternatively, exploring such patterns with bilateral trade data and other financial indicators, including inflation and exchange across currencies), b) persisting to collaborate with academics that I had the opportunity to work with during my PhD (e.g., exploring a safe operating space for human identity from a systems perspective), and c) actively engaging with transdisciplinary projects (i.e., in an integrative scientific engagement with actors from both inside and outside academia), such as my current plans of postdoctoral research with the University of York (as a researcher on a NERC funded project called SysRisk – ‘systemic environmental risk analysis for threats to UK recovery from COVID-19’) and the University of Reading (as a researcher on a NERC-funded project called EMPOWER – ‘citizen and community adaptation to systemic risks from climate change’). In the long-term, I hope that I can expand my academic, personal, and communication portfolio to pursue opportunities in which I feel that I have real-world impact, either inside or outside of academia. In other words, I plan to focus on what I can influence directly according to my own actions, whilst adapting and transforming to adversities to increase the chances of building a desirable and collective sense of resilience to avoid falling into ‘lock-in’ mechanisms.

6.2 Conclusion

The investigation of lock-in mechanisms in global food systems has been a challenging endeavour for sustainability and food security. Throughout the four manuscripts collated in this thesis, it has delivered conceptual, analytical, and quantitative advancements to the food systems scholarship. Whilst a predominant focus on production and consumption of food has been often researched in isolation across academic disciplines, this thesis collectively emphasised an inquiry into the links between resilience, sustainability, and transformational change in food systems from an interdisciplinary and holistic perspective. As a body of work, therefore, I conclude that from the lens of lock-in mechanisms it is feasible to avoid ineffective, siloed propositions to food system reform and, simultaneously, allow progress in transforming systems to trajectories that deliver multiple, long-term beneficial outcomes to society and the environment. Ambitious and transformational initiatives from this angle are sorely needed and can provide tangible insights beyond ‘business-as-usual’ or ‘incremental-adaptations’ initiatives with a focal point on increasing yields.

This thesis aimed to be a step in the pursuit of an interdisciplinary and tangible understanding of the challenges and opportunities embedded to contemporary food systems. The findings from manuscript 1 (chapter 2) and manuscript 2 (chapter 3) supported the interdisciplinary importance of the concept of lock-in mechanisms to navigate the intricate foundations of social-ecological systems for transformation towards sustainable development. In the manuscripts 3 (chapter 4) and 4 (chapter 5), an empirical investigation of global food systems enabled a quantitative comparison between distinct paradigms inherent in food research (i.e., a paradigm of systemic efficiency and of systemic food risks, respectively), which are often viewed in a fragmented manner across academic disciplines. Although challenging, it was found that the bridging concept of ‘lock-in mechanisms’ and the integrative models developed in this thesis can help to unlock a comprehensive understanding of the complex and intertwined dynamics of food systems research and practice. In other words, this research indicates that it’s not only extremely hard to change, but also not much attention has been paid to our illpreparedness for the consequences of not changing. This thesis represents a small contribution to the potential of changing food systems.

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APPENDIX 1

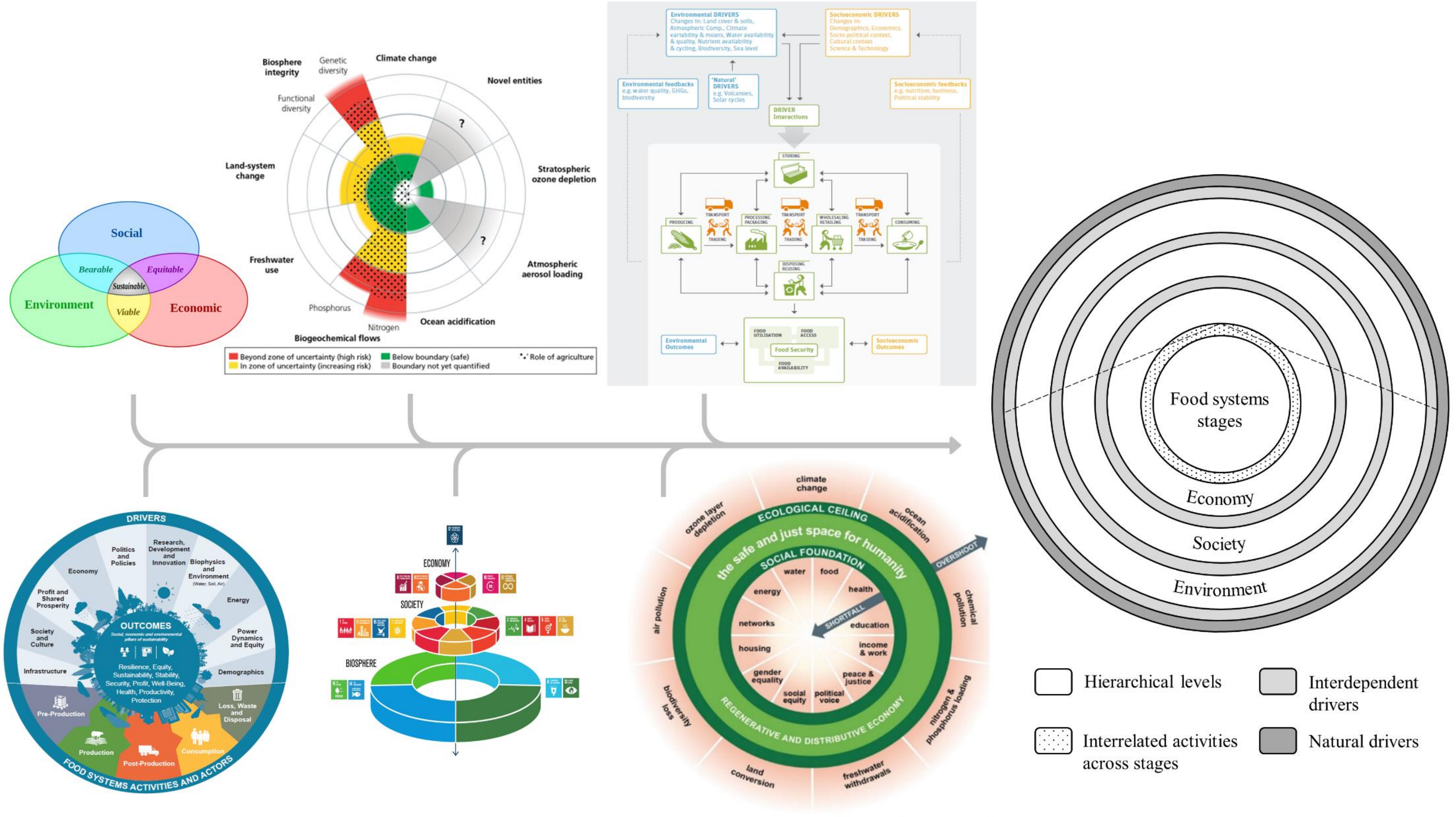
SUPPLEMENTARY MATERIAL TO CHAPTER 1

Introduction

This appendix includes:

- Supplementary Figure 1.1 – Evolution of the conceptual framework of food systems.

Supplementary Figure 1.1 – Evolution of the conceptual framework of food systems.



(continued from previous page) – The conceptual framework of food systems, its hierarchical levels, interdependent drivers, interrelated activities, and natural drivers are illustrated at the right corner of the figure. The conceptual inspirations for the design of to the framework are: the three pillars of sustainability at the top left – economy, society, and environment (WCED, 1987); the Planetary Boundaries framework at the top centre (Steffen, Richardson, et al., 2015) an illustration of food systems activities and outcomes at the top right (Ingram, 2016); the food system's interrelated components, processes, and activities (IOM & NRC, 2015); the "wedding cake" sketch of how food connects the Sustainable Development Goals at the bottom centre (Rockström & Sukhdev, 2016); and the Doughnuts economics model at the bottom right (Raworth, 2017).

APPENDIX 2

SUPPLEMENTARY MATERIAL TO CHAPTER 2

Towards a bridging concept for undesirable resilience in social-ecological systems.

This appendix includes:

- Supplementary results to chapter 2 – Scopus.
- Supplementary Table 2.1 – Details of sOcioLock-in interdisciplinary workshop and participant list.
- Supplementary Table 2.2 – Total number of papers published using the terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Scopus subject areas published between 1970 and 2018.
- Supplementary Table 2.3 – Standardised number of papers published using terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across three broad Web of Science research categories from 2000 to 18.
- Supplementary Table 2.4 – Ecological indices of richness, abundance, and equitability (evenness) for standardized number of papers published using terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords between 2000-2018 across nine specific Web of Science research areas.
- Supplementary Table 2.5 – Total number of papers published using *resilience*, *lock-in*, and *undesirable resilience* in their title, abstract, and/or keywords assigned across twenty specific Web of Science research areas between 2000-

2018 (contained in Social Sciences and Life Sciences & Biomedicine broad research categories).

- Supplementary Figure 2.1 – Diagram of literature analysed according to categorization defined in Web of Science and Scopus databases.
- Supplementary Figure 2.2 – Standardised number papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Scopus subject areas from 2000 to 18.
- Supplementary Figure 2.3 – Total number of papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords in Web of Science and Scopus from 2000 to 18.
- Supplementary Figure 2.4 – Comparison of standardised number of papers published using terms ‘resilience’, ‘lock-in’, and ‘undesirable resilience’ between two broad Web of Science research categories from 2000 to 18: Social and Life Sciences & Biomedicine.
- Supplementary Figure 2.5 – Quadrant of essential characteristics of ‘lock-in’ mechanisms: reversibility and plausibility to overcome problems.

Appendix 2

Supplementary results to chapter 2

In Scopus, total number of papers using ‘resilience’ in their abstract, title or keywords published from 2000–18 was 225,840 compared with 27,595 for ‘undesirable resilience’ and its synonyms combined. The two terms synonyms of undesirable resilience most commonly mentioned were ‘lock-in’ (12,197 papers) and ‘path dependency’ (8,259 papers)—same for Web of Science—while ‘maladaptation’ was third (5,817 papers).

In terms of evenness of use across subject areas, Supplementary Figure S3 demonstrate that all terms synonyms of undesirable resilience were used unevenly in comparison to ‘resilience’ CV value (0.69; reflecting the most even distribution across disciplines). Synonyms of undesirable resilience most evenly used across disciplines were: ‘social trap’ (CV = 0.83), ‘institutional inertia’ (CV = 0.96), and ‘maladaptation’ (CV = 1.1), ‘path dependency’ (CV = 1.11), and ‘lock-in’ (CV = 1.12).

Supplementary Table 2.1

sOcioLock-in - Understanding the undesirable resilience in social-ecological systems driving biodiversity loss.

Description: Intensive food production systems are rapidly expanding around the globe and driving a loss of biodiversity. Despite efforts to address the negative impacts of these systems and transition them to more sustainable states, they appear highly resistant. This working group took an interdisciplinary systems perspective to identify mechanisms that 'lock-in' food systems to states which drive biodiversity declines. The aim was to uncover combinations of solutions that are more likely to be successful in 'tipping' systems to more sustainable states. More information at: https://www.idiv.de/sociolock-in.html

Participant list

Name	Institution	Area of Research
Asquith, Mike	European Environmental Agency	Environmental management; Integrated assessment; Knowledge development; Sustainability transitions; Environmental governance.
Boonstra, Wijnand	Stockholm Resilience Centre	Sociology; Social-historical dynamics of primary resources; Social-ecological traps; Qualitative methods; Power; Rural development.
Boyd, Emily	Lund University Centre for Sustainability Studies	Social Sciences; Environmental Sciences, Interdisciplinary; Sustainability; Resilience; Development Studies.
Delabre, Izabela	Zoological Society of London – ZSL	Sustainable supply chains; Private sustainability governance; Tropical forest conservation and development; Corporate social responsibility; Political ecology.
Denney, J. Michael	Global Environmental Governance Project / UMass Boston	Agricultural economics; Land governance; Land-use planning; Value chain development.
Dornelles, André	University of Reading	Epidemiology and diagnosis methods; Sustainability and resilience of food systems.
Grimm, Volker	Helmholtz Centre for Environmental Research - UFZ	Ecological modelling, Pattern-oriented modelling; Individual-based and agent-based modelling; Ecological theory and concepts; Standards for model communication and formulation.
Jentsch, Anke	University of Bayreuth	Disturbance ecology; Effects of climatic extreme events on biodiversity; Land use change and

		biodiversity in cultural landscapes; Natural risks, fire ecology and disaster research.
Nicholas, Kimberly	Lund University Centre for Sustainability Studies	Climate change; Sustainable agriculture; Wine; Ecosystems services; Land use.
Oliver, Tom	University of Reading	Land use and climate change on biodiversity; Spatiotemporal indicators for biodiversity and ecosystem services; Biodiversity and the resilience of ecosystem function.
Schröter, Matthias	Helmholtz Centre for Environmental Research - UFZ	Spatial ecosystem service assessments; Spatial priority setting for joint conservation of biodiversity and ecosystem services; Integrated valuation of ecosystem services; Theoretical-conceptual development of ecosystem services; Assessments of ecosystem services at the science-policy interface.
Seppelt, Ralf	Helmholtz Centre for Environmental Research - UFZ	Land resources management based on integrated simulation and modelling systems; Model development and integration; System analysis; Simulation of environmental systems.
Settele, Josef	Helmholtz Centre for Environmental Research - UFZ	Conservation and evolutionary biology of insects; Biodiversity and land use; Interdisciplinary cooperation and project co-ordination in biodiversity.
Shackelford, Nancy	Colorado University at Boulder	Applied community ecology; ecological resilience; functional ecology; restoration science.
Standish, Rachel	Murdoch University	Management and restoration of native ecosystems; Community assembly; Ecological thresholds; Seedling recruitment; Resilience; Restoration ecology; Urban ecology.
Tambang Yengoh, Genesis	Lund University Centre for Sustainability Studies	Earth and related environmental sciences; Social sciences; Interdisciplinary, environmental sciences related to agriculture and land-use; Land resources; Agriculture, Africa; Farming; Remote sensing; Land degradation.

Supplementary Table 2.2 – Total number of papers published using the terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Scopus subject areas published between 1970 and 2018.

	Total papers published		Terms									
			Resilience		Undesirable resilience		Path dependency		Lock-in		Social Trap	
Subject Area	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18
Medicine (HS)	6,887,448	7,137,892	421	37,214	0	0	2	198	182	844	10	35
AGRI (LS)	1,093,063	2,401,417	480	34,894	0	0	2	201	36	451	11	24
EART (PS)	872,687	1,297,708	237	12,977	0	0	17	273	96	833	6	8
ENVI (PS)	847,166	1,468,864	514	39,018	0	0	17	1,071	108	1,910	45	96
ARTS (SS)	475,677	896,845	86	8,768	0	0	8	338	45	359	21	57
BUSI (SS)	220,691	684,934	124	8,428	0	0	28	1,814	194	2,665	57	116
ECON (SS)	156,398	451,082	51	5,228	0	0	42	980	242	1,917	26	71
Psychology (SS)	420,729	662,637	292	29,070	0	0	8	126	20	300	102	102
Social Sciences (SS)	931,341	1,977,910	450	50,243	0	0	63	3,258	208	2,918	128	351

	Terms											
	Institutional inertia		Maladaptation		Social-ecological trap		Unhelpful resilience		Wicked resilience		Perverse Resilience	
Subject Area	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18	1970–99	2000–18
Medicine (HS)	0	10	672	2,273	0	0	0	0	0	0	0	0
AGRI (LS)	0	19	73	880	0	1	0	1	0	1	0	0
EART (PS)	2	18	9	107	0	0	0	0	0	1	0	4
ENVI (PS)	8	108	27	566	0	1	0	1	0	1	0	7
ARTS (SS)	3	17	48	141	0	0	0	0	0	0	0	0
BUSI (SS)	6	31	6	61	0	0	0	0	0	0	0	0
ECON (SS)	8	45	7	53	0	0	0	0	0	0	0	0
Psychology (SS)	1	7	490	925	0	0	0	0	0	0	0	0
Social Sciences (SS)	34	180	289	811	0	0	0	0	0	0	0	9

Abbreviations: Health Sciences (HS); Life Sciences (LS); Social Sciences (SS); Physical Sciences (PS); Agricultural and Biological Sciences (AGRI); Earth and Planetary Sciences (EART); Environmental Science (ENVI); Arts and Humanities (ARTS); Business, Management and Accounting (BUSI); Economics, Econometrics and Finance (ECON).

Supplementary Table 2.3 – Standardised number of papers published using terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across three broad Web of Science research categories from 2000 to 18.

Term	Broad Research Categories	Standardised number of publications	Percentage of publications per term
Resilience	Arts & Humanities	1,141	7.9%
	Social Sciences	6,136	42.4%
	Life Sciences & Biomedicine	7,202	49.7%
Path dependency	Arts & Humanities	210	20.6%
	Social Sciences	584	57.2%
	Life Sciences & Biomedicine	227	22.3%
Institutional inertia	Arts & Humanities	38.6	20.5%
	Social Sciences	120	63.5%
	Life Sciences & Biomedicine	30.3	16%
Lock-in	Arts & Humanities	287	18.2%
	Social Sciences	892	56.5%
	Life Sciences & Biomedicine	400	25.3%
Perverse resilience	Arts & Humanities	4.3	44.6%
	Social Sciences	1.6	17%
	Life Sciences & Biomedicine	3.7	38.4%
Social trap	Arts & Humanities	9.3	0.9%
	Social Sciences	494	47%
	Life Sciences & Biomedicine	547	52.1%
Maladaptation	Arts & Humanities	1.6	0.4%
	Social Sciences	124	31.8%
	Life Sciences & Biomedicine	265	67.8%
Social-ecological trap	Arts & Humanities	0	-
	Social Sciences	0.8	5.8%
	Life Sciences & Biomedicine	13.3	94.2%
Unhelpful resilience	Arts & Humanities	0	-
	Social Sciences	1.6	35.7%
	Life Sciences & Biomedicine	3	64.3%
Undesirable resilience	Arts & Humanities	0	-
	Social Sciences	12.3	22.3%
	Life Sciences & Biomedicine	42.8	77.7%
Wicked resilience	Arts & Humanities	8.6	26.3%
	Social Sciences	4.1	12.6%
	Life Sciences & Biomedicine	19.9	61.1%

Numbers of papers are standardised by dividing the total number of papers in a given broad research categories x 10^6 (i.e., reflecting the number of papers including these terms per million papers published in the research area).

Supplementary Table 2.4 – Ecological indices of richness, abundance, and equitability (evenness) for standardized number of papers published using terms resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords between 2000-2018 across nine specific Web of Science research areas.

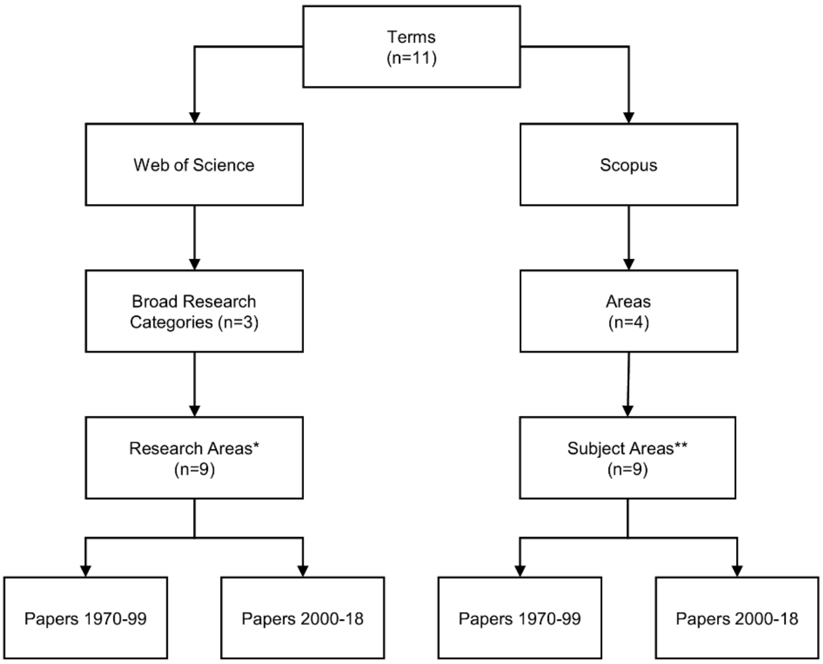
Term	Richness $D^R = n$ ($\alpha = 0$)	Shannon-Wiener Index; D^{SW} ($\alpha = 1$)	Simpson's Index; D^S ($\alpha = 2$)	Berger-Parker Index; D^{PB} ($\alpha = +\infty$)
Resilience	9	0.89	0.83	0.25
Undesirable resilience	5	0.83	0.67	0.51
Path dependency	9	0.82	0.80	0.28
Lock-in	9	0.83	0.79	0.37
Social trap	9	0.87	0.82	0.30
Institutional inertia	8	0.75	0.75	0.33
Maladaptation	9	0.79	0.78	0.30
Social-ecological trap	3	0.53	0.30	0.83
Unhelpful resilience	4	0.97	0.73	0.37
Wicked resilience	7	0.80	0.71	0.48
Perverse resilience	4	0.94	0.72	0.35

Research areas explored to quantify richness are: History, Philosophy, Psychology, Business & Economics, Government & Law, Sociology, Behavioral Sciences, Agriculture, and Environmental Sciences & Ecology.

Supplementary Table 2.5 – Total number of papers published using *resilience*, *lock-in*, and *undesirable resilience* in their title, abstract, and/or keywords assigned across twenty specific Web of Science research areas between 2000-2018 (contained in Social Sciences and Life Sciences & Biomedicine broad research categories).

	Total publications	Terms		
Research Area		Resilience	Lock-in	Undesirable resilience
Social Sciences (SS)				
Area Studies	32,683	210	20	0
Business & Economics	489,535	1,712	852	9
Development Studies	26,355	444	44	0
Geography	120,465	1,516	174	3
Government & Law	167,688	518	167	0
International Relations	49,928	378	77	0
Psychology	541,429	5,136	94	6
Social Issues	26,615	163	16	0
Sociology	79,673	591	24	2
Urban Studies	29,469	451	56	0
Life Sciences & Biomedicine (LS)				
Agriculture	475,465	1,144	57	5
Anthropology	50,869	318	13	0
Behavioral Sciences	90,488	304	20	0
Biodiversity & Conservation	70,502	955	9	7
Developmental Biology	66,646	39	8	0
Environmental Sciences & Ecology	862,470	9,009	515	61
Evolutionary Biology	91,376	319	13	3
Marine & Freshwater Biology	193,729	1,632	15	7
Zoology	208,469	244	17	0
Public, Environmental & Occupational Health	379,917	1,843	35	1

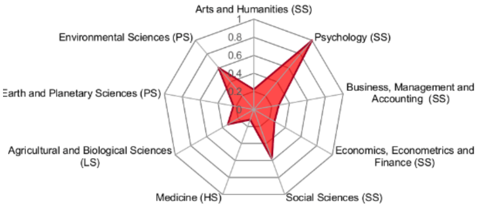
<u>Supplementary Figure 2.1</u> – Diagram of literature analysed according to categorization defined in Web of Science and Scopus databases.



In Web of Science, broad research categories are Arts & Humanities (AH), Social Sciences (SS) and Life Sciences & Biomedicine (LS). * Research Areas are: History, AH; Philosophy, AH; Business & Economics, SS; Government & Law, SS; Psychology, SS; Sociology, SS; Agriculture, LS; Behavioral Sciences, LS; Environmental Sciences & Ecology, LS. In Scopus, areas are Health Sciences (HS), Life Sciences (LS), Physical Sciences (PS) and Social Sciences (SS). ** Subject areas are: Medicine, HS; Agricultural and Biological Sciences, LS; Earth and Planetary Sciences, PS; Environmental Science, PS; Arts and Humanities, SS; Business, Management and Accounting, SS; Economics, Econometrics and Finance, SS; Psychology, SS; Social Sciences, SS. Terms searched in the databases were: *resilience; undesirable resilience; institutional inertia; path dependency; lock-in; social traps; social-ecological traps; unhelpful resilience; maladaptation; perverse resilience; wicked resilience*.

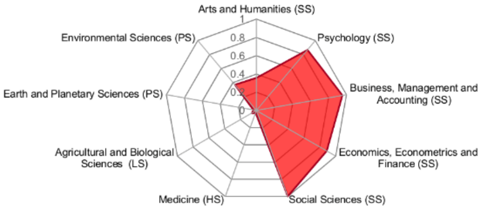
Supplementary Figure 2.2 – Standardised number papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords assigned across nine specific Scopus subject areas from 2000 to 18.

Resilience
Scale: 1= 43,870 papers per million papers



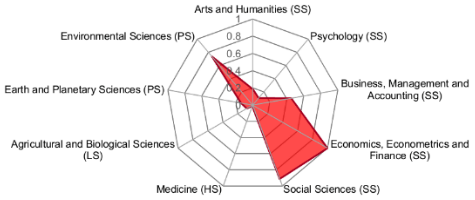
CV= 0.69

Social Trap
Scale: 1= 177.5 papers per million papers



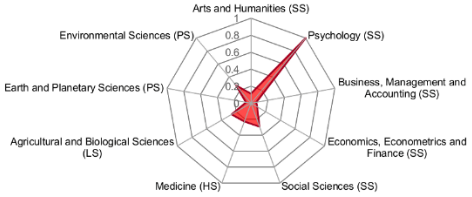
CV= 0.83

Institutional inertia
Scale: 1= 99.7 papers per million papers



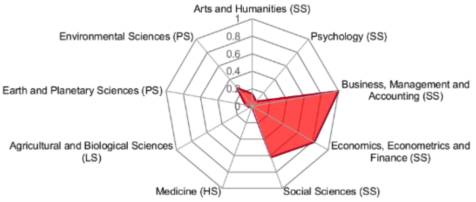
CV= 0.96

Maladaptation
Scale: 1= 1,396 papers per million papers



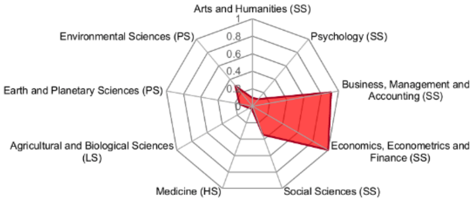
CV= 1.1

Path dependency
Scale: 1= 2,648 papers per million papers



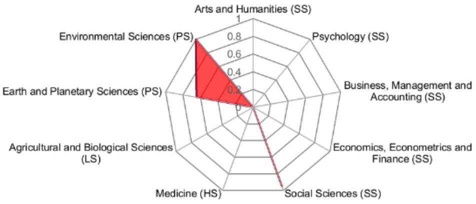
CV= 1.11

Lock-in
Scale: 1= 4,250 papers per million papers



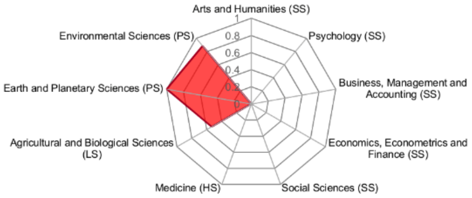
CV= 1.12

Perverse Resilience
Scale: 1= 4.76 papers per million papers



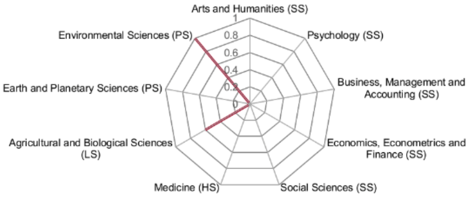
CV= 1.54

Wicked resilience
Scale: 1= 0.77 papers per million papers



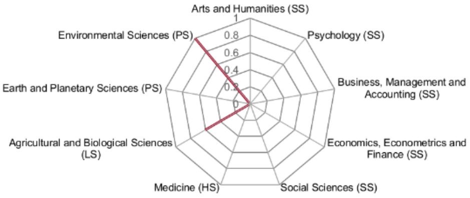
CV= 1.56

Social-ecological trap
Scale: 1= 0.68 papers per million papers



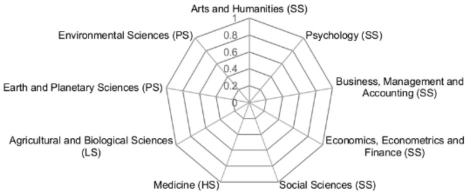
CV= 2.06

Unhelpful resilience
Scale: 1= 0.68 papers per million papers



CV= 2.06

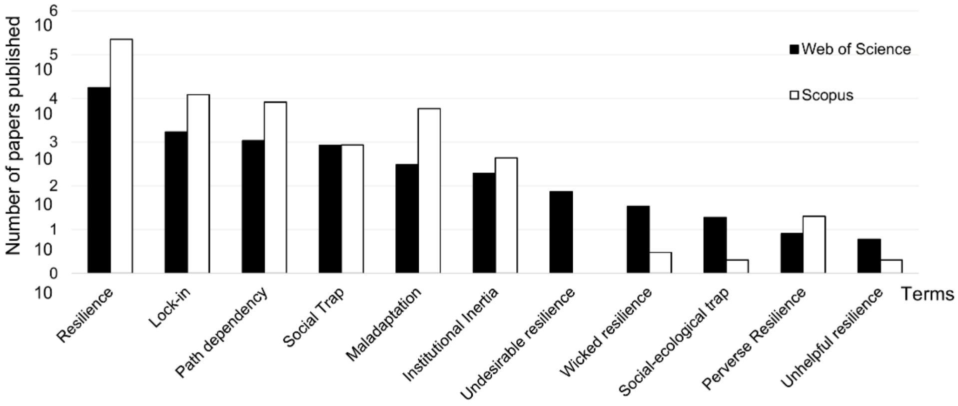
Undesirable resilience
Scale: 1= 0 papers per million papers



CV= 0 (zero)

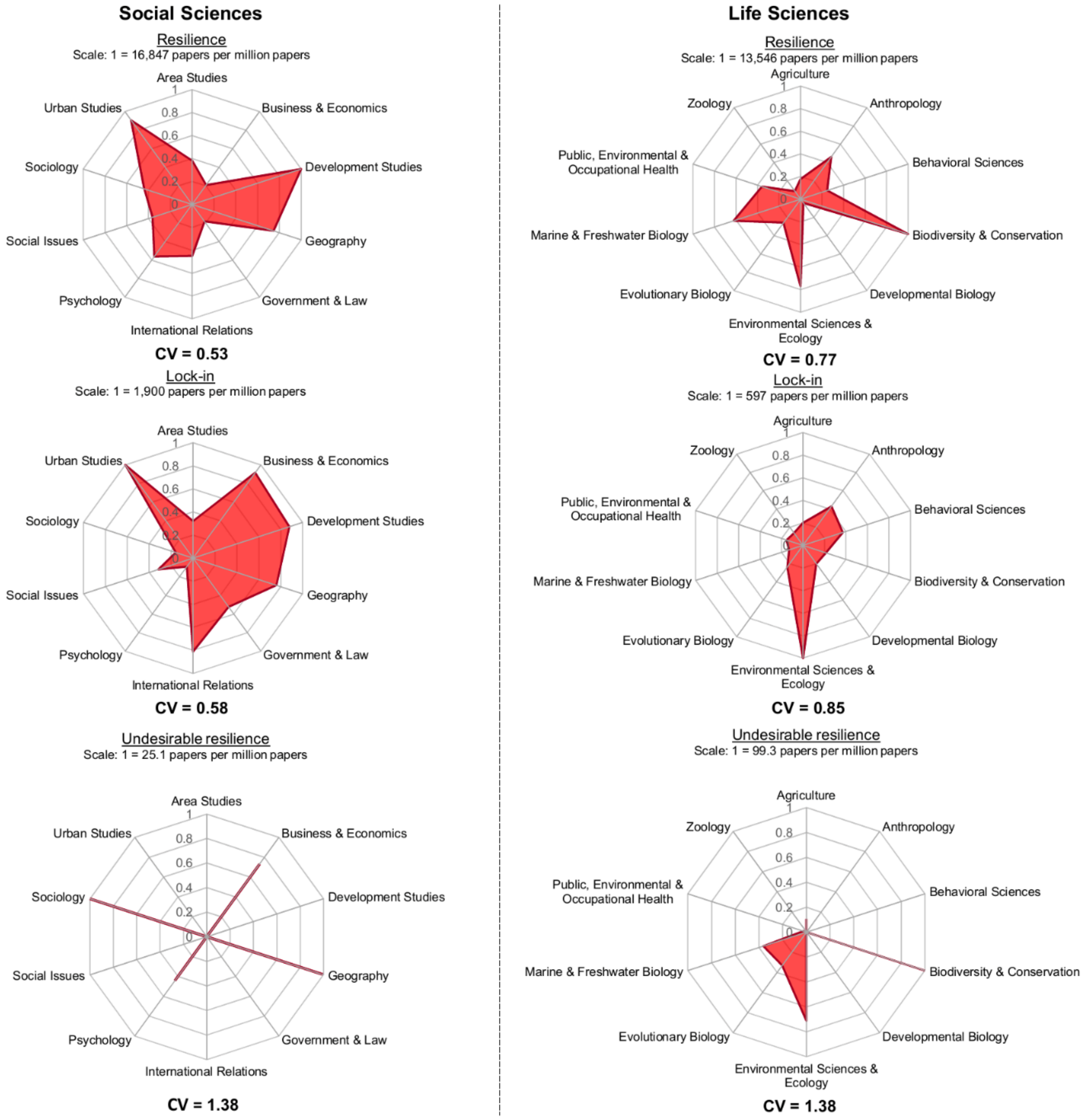
(continued from previous page) Numbers of papers per million papers are plotted through a proportional scale ranging from 0 to 1, the latter representing the maximum value of standardised number of publications for each term across subject areas. Radar graphs are ordered by CV (coefficient of variation) value, reflecting increasingly uneven use across the different subject areas. Abbreviations: SS – Social Sciences; HS – Health Sciences; LS – Life Sciences; PS – Physical Sciences.

Supplementary Figure 2.3 – Total number of papers published using the term resilience and synonyms of undesirable resilience in their title, abstract, and/or keywords in Web of Science and Scopus from 2000 to 18.



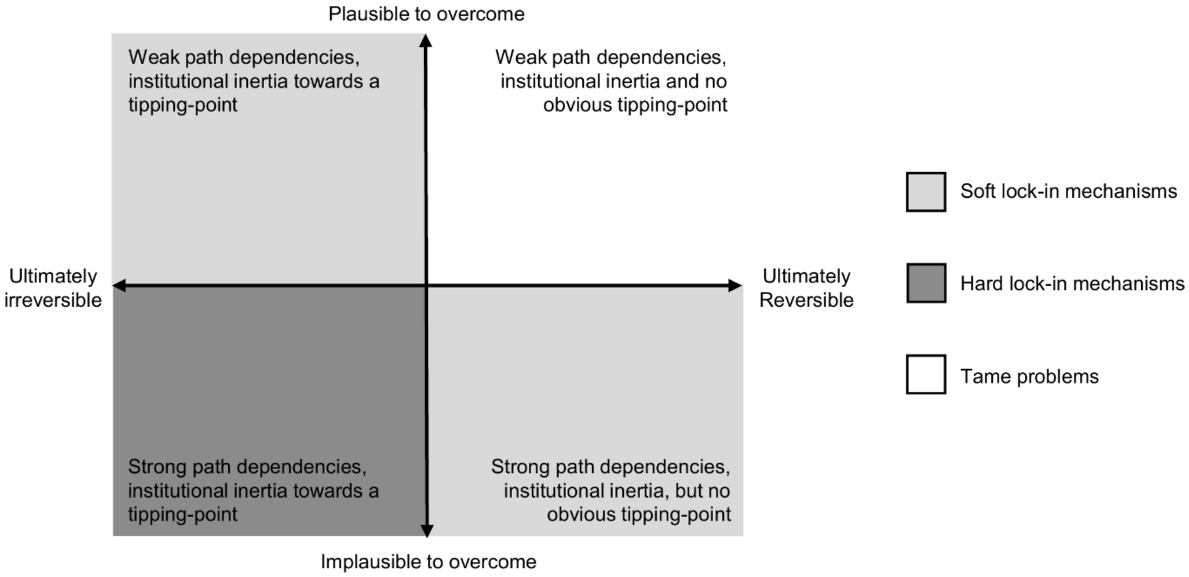
Bars are ordered by number of publications in Web of Science. Note, that the number of papers are presented on a logarithmic scale.

Supplementary Figure 2.4 – Comparison of standardised number of papers published using terms ‘resilience’, ‘lock-in’, and ‘undesirable resilience’ between two broad Web of Science research categories from 2000 to 18: Social and Life Sciences & Biomedicine.



Ten different specific research areas compose each broad research category. Numbers of papers per million papers are plotted through a proportional scale ranging from 0 to 1, the latter representing the maximum value of standardised number of publications for each term across research areas. Radar graphs are ordered by CV (coefficient of variation) value, reflecting increasingly uneven use across the different research areas.

Supplementary Figure 2.5 – Quadrant of essential characteristics of 'lock-in' mechanisms: reversibility and plausibility to overcome problems.



Reversibility refers to the capacity of social-ecological systems to recover functions and services after exceeding "safe-limit" thresholds, planetary boundaries or tipping points (Newbold et al., 2016). Although there are variable degrees of uncertainty (Oliver, 2016) and non-linearity (Milkoreit et al., 2018), if trajectories within parts of a system are likely to lead to irreversible consequences, then interventions aiming to prevent and/or mitigate outcomes are required (IPCC, 2014). IPCC (2018), for example, concluded with high confidence that global warming of ≥2°C above pre-industrial levels carries an increasing "*…risk of irreversible loss of many marine and coastal ecosystems*" (p. 10), whilst, from a perspective of stunting in early childhood, de Onis and Branca (2016) emphasized that "*the severe irreversible physical and neurocognitive damage that accompanies stunted growth poses a major threat to human development*" (p. 23). In parallel, plausibility refers to the likelihood of implementing reconcilable interventions aiming to transform trajectories, which may or may not lead to irreversible consequences. Factors impairing the plausibility of overcoming persistent dynamics include concentration of power (Woodall & Shannon, 2018), siloed approaches (i.e., artificially deconstructing intertwined parts of a system in isolation - Reyers et al., 2018), and various underlying cultural and/or epistemic lock-ins - e.g., resilient production and consumption of inefficient, resource-intensive foods, particularly red and processed meat (Bruce & Spinardi, 2018; Heinz & Lee, 1998), persistent justifications for excluding women from education and society (Moaddel, 1998); or resilient preconceptions about science and policy (Sunstein et al., 2017). Rather than addressing these lock-ins as mere consequences of lack of awareness or epistemic gaps, exploring environmental nudges, conscious and non-conscious interacting processes seems to enable (unlock) potential leverage points for transformation (Hassink, 2005; Marteau, 2018). See main text for further discussion.

APPENDIX 3

SUPPLEMENTARY MATERIAL TO CHAPTER 3

Breaking lock-ins for social-ecological transformations.

This appendix includes:

- Supplementary Table 3.1 – Summary of findings in the four case studies: pollinators decline, Negative Emission Technologies (NETs) fixation, plastic pollution, and meat overconsumption.

Supplementary Table 3.1 – Summary of findings in the four case studies: pollinators decline, Negative Emission Technologies (NETs) fixation, plastic pollution, and meat overconsumption.

	Pollinators decline	NETs fixations	Plastic pollution	Meat overconsumption
Current state	• Pollinators are a key component of global biodiversity, provide vital ecosystem functions by pollinating crops and wild plants. • 75%-95% of all flowering plants on earth need a certain degree of pollination. • Bees are capable of increasing yield in 96% of animal-pollinated crops. • 87 of the 115 most important global crops consumed by humans rely on animal pollination to some degree. • About 5-8% of global crop production, with an annual market value of 235 billion - 577 billion US dollars is directly attributable to animal pollination.	• 1.5 –2 degrees and temperature have already exceeded thresholds. • Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. • Negative emissions technologies have not been demonstrated to perform at large scale (storage and permanence) convincingly and reliably.	• 1950-2015: 8300 Mt of plastic produced, and 6300 Mt wasted. Out of the waste, 600 Mt recycled, 800 Mt incinerated, and 4900 Mt accumulated in landfills or in the natural environment. • 2010: 270 Mt produced, 275 Mt wasted, and 12.7 Mt entering the oceans (0.01 to 0.1 Mt of plastics in surface waters). • Recycling: Only 100Mt of all the recycled plastics are currently in circulation.	• Livestock dominates 83% of the world’s farmland and is responsible for 58% of foods’ GHG emissions, but only provide 37% of proteins and 18% of calories for human consumption. • Animal feed is responsible for 67% of agriculture-driven deforestation and covers 1/3 of the existing arable land. • 25% of the world’s ice-free land is used for grazing. • Livestock is responsible for 14.5% to 18% of all anthropogenic GHG emissions. • Producing 5% of calories generates 40% of food’s environmental burden.
Trends	• Evidence of recent declines in both wild and domesticated pollinators, and parallel declines in the plants that rely upon them.	• Trends towards 2°C over 450ppm. • Upward trajectory of global CO2eq emissions. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (high confidence).	• Persistent increase in plastic production and insufficient management of waste. • By 2025: between 92.8 Mt to 247.5 Mt cumulative waste in the oceans (from a total of 618.7 Mt of mismanaged waste). • By 2050: 9000 Mt recycled, 12,000 Mt incinerated, and 12,000 Mt accumulated in landfills or in the natural environment	• Increasing demand for animal foods. • Even under ambitious scenarios (e.g., synergistic improvement of diet change, technological advances, and food loss and waste reduction) and optimistic estimates of income and population growths, it will be considerably challenging to keep food systems within planetary boundaries.

Risks	• Mass breeding and managed movement of pollinators has resulted in the geographic spread of disease (especially parasitic mites, e.g., Varroa jacobsoni and Varroa destructor) to local pollinators. • Habitat conversion and fragmentation pose major problems for populations of pollinator species. • Global agricultural intensification accompanied by the proliferation and misuse of chemicals. • Global, regional, and local climate changes (shifts in temperature and precipitation, concentrations of CO2, etc.) can alter or disrupt plant-pollinator relationships and their ranges.	• Extreme weather disasters (e.g., floods and droughts). • Adaptation and mitigation failure (for both current state and future trends). • Social, economic, and environmental side-effects of deploying NETs.	• Marine and terrestrial ecosystems pollution. • Disruption of marine ecosystem services and functions. • Micro-plastics Pcbs in humans and animals.	• Environmental impacts (e.g., GHG emissions, deforestation, freshwater abusive use, biodiversity loss, ocean's acidification, and eutrophication). • Health impacts from red and processed meat (e.g., cancer, coronary heart disease, stroke, type 2 diabetes mellitus, antibiotic resistance, and overall mortality).
Risks for whom?	• Pollinators' resilience (quantity, diversity, and migration). • People under food insecurity (mainly, due to scarcity and instability). • Ecosystems functions and services.	• Results indicate that groups with limited adaptive capacity, including those in poverty and non-white populations, are at higher risk for heat exposure, suggesting an emerging concern of environmental justice as it relates to climate change.	• Human and planetary health (all living beings).	• Animals (livestock and those impacted by environmental burden). • Malnourished people (mainly, due to excessive consumption). • Water-scarce communities. • Populations most vulnerable to climate change impacts.
Key lock-in mechanisms				
Personal	• Increased demand of high-energy foods by large proportions of the global population. • Ignorance and apathy to the production of agriculture produce	• 'Techno-optimism' (solutions will be available soon). • Risk perception (relying too much on the unknown at the expense of changing the known)	• Cognitive dissonance (we all consume plastics). • Ignorance and apathy. • Lack of empathy • Comprehension of the pollution's scale (risk perception).	• Tastes and preferences. • Beliefs and values (e.g., 'masculinity' and aesthetics of meat). •Alternative protein source deemed 'too radical'. • Ignorance and apathy.

	• Lack of sympathy towards or emotional connection with insects and other pollinators • Feeling of powerlessness in relation to agrochemical firms.	• Comfort (convenience of waiting for an external solution rather than taking initiative) • Lack of empathy and responsibility for 'global' phenomenon; cognitive dissonance ("I am just one person; what I do won't make a difference") • Ignorance and apathy • Alienation (existential threat; denial.	• Feasibility to design plausible solutions (e.g., efficiency of waste management or quality of alternative materials).	• Unappealing risk perception (complex and 'distant' consequences of eating behaviours). • Cognitive dissonance. • Neglected animal welfare.
Political	• Commoditization of pollinators - agricultural export commodities have developed into an essential source of income, employment, and government revenues. • Habitat degradation and loss leading to wild pollinator extinctions. • Climate change – can affect species distributions and phenologies, and hence, survival under new ecosystem conditions.	• Profit maximization (earning from both manufactured capital of CO2 emissions and NETs rather than reducing CO2 emissions). • "Disaster capitalism" (emotional/physical distraction to resist current injustices) • Co-option / No society • Reinforcement of business-as-usual • Diversion of attention (promoting focus on NETs while neglecting transformation options as priority) • Inequity (in general, groups with limited adaptive capacity are the least responsible for polluting in the first place).	• Profit maximization. • Lack of accountability (nationally and internationally). • Fragmentation and durability of plastics in the ocean. • Only a fraction of the pollution is found in surface water.	• Lobbying power of the food industry. • Low-cost land conversion/economies of scale • Deforestation (e.g., driven by feed). • Water stress (e.g., freshwater use). • Land mismanagement. • Greenhouse gases emissions. • Income and population growth following certain (unsustainable) development pathways.
Practical	• High-input intensive farming leading to increase in agrochemical use. • Large-scale land use changes and conversion to industrial monocultures. Farmers caught in a system of intensification and continuous	• Perception of abstract and technical nature of NETs, closes down democratic decision-making on deployment of technologies • 'Comfortable' current behaviours • Lack of perceived convenient mitigation mechanisms • Routine, business-as-usual	• Routines (e.g., design, investments, and path dependency). • Waste management can't cope with increasing production. • Preferable choice (e.g., cheaper and resistant). • Lack of appropriate alternatives (e.g., for food packaging).	• Failure to apply existing solutions in the production stage (e.g., Estimated Breeding Values). • Non-incorporation of externalities (e.g., price of output does not reflect the costs of environmental inputs). • Path dependencies.

	appliance of agro-chemicals and fertilizers.	• Culture influencing behaviour • Dependence on CO2 (e.g., dependence on natural gas in the house-heating sector in Europe)	• Inequality in waste generation (higher in developed countries.	• Power and gender inequality (e.g., within farms and between small farms and big business). • Increasing demand for meat in developing countries. • Culture of meat (e.g., protein intake or traditional events).
Transformation trajectories (making change possible; ‘bending the curve’)	• National and international effort: (i) National Pollinator Week, and the National Strategy to Promote the Health of Honeybees and Other Pollinators in the USA; (ii) Global Action on Pollination Services for Sustainable Agriculture International Pollinators Initiative of the FAO; (iii) EU Pollinators Initiative in the European Union. • Farming practices: (i) Integrate and maintain uncultivated patches of vegetation such as field margins with extended flowering periods on farmlands to support pollinators; (ii) Extensify grassland management practices to increase flower abundance. (iii) Support diversified farming systems, crop rotations, and organic farming practices to limit the chemical burden on the farming environment. Support pollinator-friendly practices in the management of urban green spaces. • Raising awareness and improving collaboration: Examples (i) encouraging methodological advances in monitoring pollination	• Science well established, yet almost nothing is done practically (e.g., Bangladesh). • California. • UK community renewable, Denmark • Greta Thunberg – social movement but 30 years behind. • IPCC (Intergovernmental Panel on Climate Change); binding targets. • Use of precautionary principle and democratic engagement for use of NETs.	• Consumer changes (e.g., reusable bags or decrease consumption of products with plastic packaging). • Stockholm Convention (UN, 2001). • The Honolulu Strategy (UNEP and US NOAA, 2011). • Global Plastics Platform (UNEP, 2018). • EU Plastics Strategy (European Commission, 2018). • Global Plastic Action Partnership (World Economic Forum, 2018). • Banning of single-use plastics at national level (e.g., Canada, by 2021).	• Citizen and consumer changes (e.g., vegetarian, vegan, or flexitarian diets). • Adequate information for consumers (e.g., food labelling and dietary guidelines). • Platforms of international collaboration for scientific assessment and evidence-based institutions (e.g., EAT-Lancet and IPBES). • Multi-stakeholders and multi-action frameworks to healthy diets from sustainable food systems (e.g., Nuffield Ladder of Policy Intervention). • Tax on red and processed meat. • Sustainable intensification (e.g., government incentives).

	services; (ii) incorporate ecosystem services into national and regional decision making; (iii) coordinate awareness and research action across national borders.			
Critical shift factors				
Personal	• Systems transformation: (i) Raise biological, moral and cultural arguments for pollinator conservation to complement the dominant economic and ecosystem arguments. • Advocacy and education: (i) Education and sensitization on land users on practices that can support or hinder pollination services; (ii) Translate scientific research into accessible forms for relevant land user groups and public audiences.	• Family planning and education • Myth busting about the costs of renewables. • Advocacy and education: understanding of the carbon footprint and major emitters. • Recognising and promoting individual agency to act, democratising interventions.	• Collective values and worldviews (e.g., equity, prosperity, and partnership). • Systems thinking (interconnectivity of ecosystems and boundaries). • Consciousness of impact on individual animals (e.g., stranded whales).	• Conscious processes (e.g., animal welfare). • Systems thinking (e.g., impact on different ecosystems: the amount of deforestation driven by feed). • Resource-efficiency (how much of diverse resources invested as input to generate an output).
Political	• Removing regulatory hurdles to sustainable landscape development that favours pollinator health. • Government lobbying for necessary legislation to incentivize sustainable landscape management practices. • Stricter regulation regimes for vetting and approving agricultural chemical use.	• UNFCCC PA. • Alternative alliances that push for social and technological innovations and more equitable governance. • Fossil fuel divestment • Carbon tax • De-mystifying "high-tech" solutions and opening up policy spaces to citizens.	• Social and government incentives for recycling and waste prevention. • Traditional and social-media coverage. • Facilitate national and international platforms of transparency and accountability.	• Law development and enforcement of biodiverse protected areas. • Traditional and social-media coverage. • Legitimize and operationalize evidence-based institutions (e.g., IPCC-like intergovernmental panel for sustainable food systems or UN Framework Convention on Sustainable Food Systems).
Practical	• Systems transformation: (i) Reducing chemical dependency in agricultural land use; (ii) Transitioning from intensive monocropping to low external input production systems.	• Events: Earth Day, climate strikes • Personal and public. transportation: incentivizing less polluting alternatives (e.g. electric and hybrids instead of gas for cars, prioritizing trains instead of	• Communication plus experience (e.g., documentaries and campaigns). • Education.	• Communication (e.g., documentaries and campaigns). • Education to citizens and training of health professionals (e.g., nurses, physicians).

	• Research (i) Support for research to assess and monitor trends in pollination services delivery, associated challenges, and trade-offs; (ii) Support for cross-institutional research collaboration, and research-to-policy dialogue to ensure scientific research translates to policy on pollination service delivery. • Financial instruments: (i) Government subsidies or tax incentives for pollinator-friendly land use activities and products.	airplanes for short to mid-distance journeys). • Large-scale energy efficiency measures and behaviours; mass decarbonisation; investments in renewable energy. • Collective action and political engagement of citizens on climate. • Reducing consumption is key (alternative measures of human development?).	• Prevention is key (e.g., waste management at the source: 'source reduction'). • Science & technology (e.g., innovations to remove and prevent plastic pollution or robust assessments of the amount of plastic pollution in different ecosystems). • Local initiatives (e.g., plastic collector, compactor machine, and sparked collective action). • State-level initiatives (e.g., ban of single-use items or charges for plastic bags. • Collective action.	• Implementation of available solutions respecting local contexts and traditions (e.g., improved resources and waste management). • Demonstrate healthy alternatives for the people and the environment. • Reduce consumption of red and processed meat. • Apply the Nuffield Ladder of Policy Intervention healthy diets from sustainable food systems (i.e., involving roles of citizens, government, industry). • Collective action.
Towards sustainable and equitable goals	• SDG 1 • SDG 2 • SDG 3 • SDG 8 • SDG 15	• SDG 7 • SDG 11 • SDG 12 • SDG 13; Target 13.3 • SDG 15	• SDG 6 • SDG 11 • SDG 12; Target 12.5 • SDG 14; Target 14.1	• SDG2; Targets 2.1 to 2.5 • SDG 3; Target 3.4 • SDG6; Target 6.4 • SDG 12; Target 12.2 • SDG 15; Targets 15.1, 15.2, and 15.5

Abbreviations: NETs – Negative Emissions Technologies; Pcbs – Polychlorinated biphenyls; UNFCCC: United Nations Framework Convention on Climate Change.

APPENDIX 4

SUPPLEMENTARY MATERIAL TO CHAPTER 4

Transformation archetypes in global food systems.

This appendix includes:

- Supplementary methods to chapter 4
  - A4.1 Overview
    - Supplementary Figure 4.1 – Flowchart of the data manipulation process.
    - Supplementary Figure 4.2 – Framework of structure and outcome metrics and their connections to the holistic model.
  - A4.2 Data acquisition
    - Supplementary Table 4.1 – Comprehensive traits of metrics attributable to stages of food systems, aspects of food security, and boundaries of planetary health.
    - Supplementary Table 4.2 – Databases explored in this study.
    - Supplementary Table 4.3 – Main characteristics of metrics used in this study: duration, unit, and source.
  - A4.3 Data preparation
    - Supplementary Table 4.4 – Filter of best fit for the metric Agricultural area.
    - Supplementary Table 4.5 – Descriptive results of structure, outcome, and socioeconomic metrics after the data preparation

        stage.
    - A4.4 Data analysis
    - A4.5 Metadata
- Supplementary results to chapter 4
    - A4.6 Descriptive results and cluster algorithm output
        - Supplementary Figure 4.3 – Cluster dendrogram and most appropriate clustering schemes for the key structure metrics.
        - Supplementary Figure 4.4 – Global trends in structure metrics across two transformation archetypes in global food systems of 161 countries from 1995 to 2015.
        - Supplementary Figure 4.5 – Global trends in outcome metrics across two transformation archetypes in global food systems of 161 countries from 1995 to 2015.
        - Supplementary Figure 4.6 – Global trends in structure metrics across four transformation archetypes in global food systems of 161 countries from 1995 to 2015.
        - Supplementary Figure 4.7 – Global trends in outcome metrics across four transformation archetypes in global food systems of 161 countries from 1995 to 2015.
        - Supplementary Table 4.6 – Rates of annual change of all structure, outcome, and socioeconomic metrics across transformation archetypes in global food systems in 161 countries from 1995 to 2015.
        - Supplementary Table 4.7 – Significance testing of all structure, outcome, and socioeconomic metrics across transformation

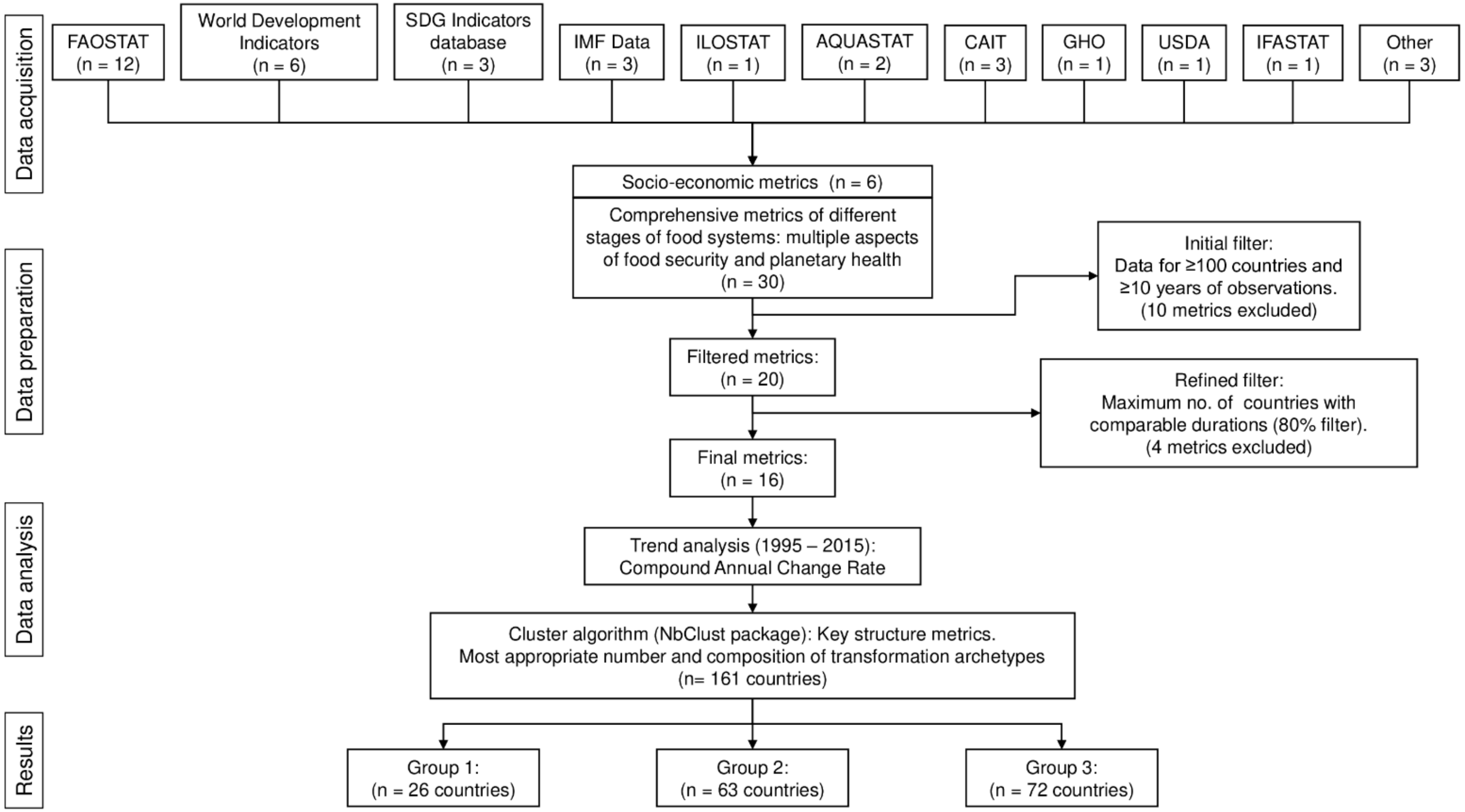
archetypes in global food systems in 161 countries from 1995 to 2015.

- A4.7 Five-year intervals analysis
    - Supplementary Figure 4.8 – Global trends in 5-year intervals of structure metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015.
    - Supplementary Figure 4.9 – Global trends in 5-year intervals of outcome metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015.
- Methodological reflections to chapter 4
- Scripts to chapter 4
    - Supplementary Table 4.8 – R scripts used in this study.

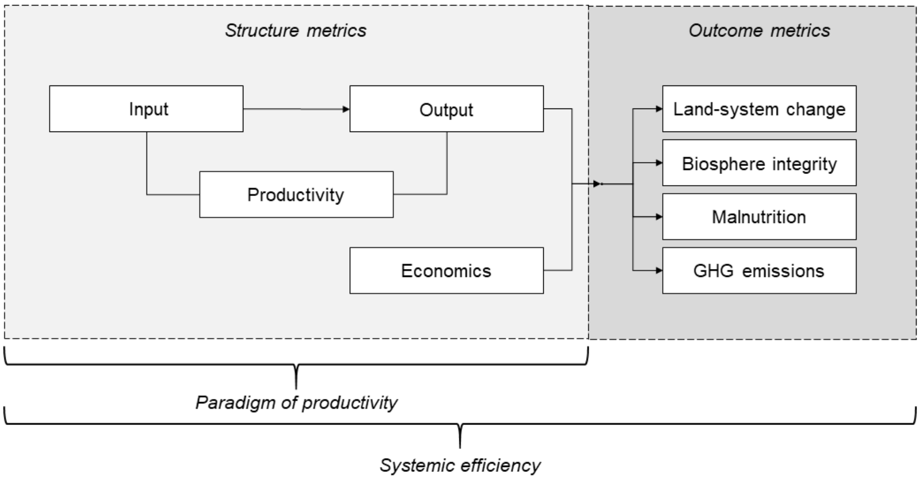
Supplementary methods to chapter 4

A4.1 Overview

All key steps of our quantitative assessment, from data acquisition to data analysis, are synthesised in the Supplementary Figure 4.1. Our model framework is illustrated in the Supplementary Figure 4.2.



Supplementary Figure 4.1 – Flowchart of the data manipulation process. In the data acquisition row, ‘n’ expresses the number of metrics from each database.



Supplementary Figure 4.2 – Framework of structure and outcome metrics and their connections to the holistic model.

A4.2 Data acquisition

In our study, we initially explored twelve open-source databases and 36 different metrics were acquired, respecting the pre-established criteria: 1) capability of measuring multiple complementary stages of the food systems (Supplementary Table 4.1), 2) data available per country, for a vast amount of countries (minimum of 100 countries), and 3) data available for a long period of time (minimum of 10 years of measured observations), preferentially on a yearly basis (e.g. from 1961 to 2015). The examined databases were FAOSTAT (from the Food and Agriculture Organization of the United Nations), World Development Indicators (from the World Bank), SDG Indicators database (from the United Nations), IMF Data (from the International Monetary Fund), ILOSTAT (from the International Labour Organization), USDA the United States Department of Agriculture), AQUASTAT (from the Food and Agriculture Organization of the United Nations), Climate Analysis Indicator Tool (from the World Resource Institute), Global Health Observatory (from the World Health Organization), United States Department of Agriculture, World Economic Outlook, IFASTAT (from the International Fertilizer Association), Global Health Data Exchange (from the Institute of Health Metrics and Evaluation), and National Footprint and Biocapacity Accounts (from the Global Footprint Network). A brief description of the collected databases is described below (Supplementary Table 4.2).

The complete description of all 36 metrics initially acquired are available in the Metadata section of the Supplementary materials and key characteristics of metrics are compiled in the Supplementary Table 4.3.

<u>Supplementary Table 4.1</u> – Comprehensive traits of metrics attributable to stages of food systems, aspects of food security, and boundaries of planetary health.

Metric	**Food systems – stages**				**Food security - aspects**				**Planetary Health – boundaries**			
	Input	Production	Supply chain	Consumption	Availability	Access	Stability	Utilization	Biosphere integrity	Land-system	Climate change	Other*
Structure metrics												
Agricultural area	X	X			X					X		
Fertilizer use	X	X			X							
Synthetic fertilizer use	X	X			X		X					X
Pesticide use	X	X			X		X		X			X
Agricultural employment	X	X										
Agricultural water withdrawal	X	X			X		X					X
Gross Agricultural Output and Value		X			X							
Agricultural Total Factor Productivity	X	X			X							
Food imports, Food exports, and ratio			X	X	X		X					
Agricultural Value Added (total and per worker)	X	X			X		X					
Agricultural Orientation Index		X	X		X		X					
Central government expenditure in agriculture, forestry, and fishing		X	X		X		X	X				
Consumer Food Price, Food			X	X		X	X	X				
Producer Food Price, Agriculture		X	X			X	X					
Domestic Food Price and Volatility			X	X		X	X	X				
Outcome metrics												
Per capita Food Supply Variability			X	X	X	X	X					
Forest area									X	X		
Red List Index	X				X		X		X			X
Obesity and Undernourishment				X	X	X	X	X				
Agricultural GHGE	X	X			X		X				X	
Land-use change and forestry GHGE	X	X			X		X			X	X	
Agriculture, land-use change and forestry GHGE	X	X			X		X			X	X	
Ecological Footprint of Consumption			X	X	X	X		X		X		X

Each ‘X’ allocated in the table represents a relevant impact on food systems stages, aspects of food security, or planetary boundaries for the structure and outcome metrics collated for this study. Abbreviations: GHGE – Greenhouse gases emissions. Other*: represent different planetary boundaries, such as freshwater use and biogeochemical flow.

Supplementary Table 4.2 – Databases explored in this study.

Database	Description	Institution
FAOSTAT	FAOSTAT provides free access to food and agriculture data for over 245 countries and territories and covers all FAO regional groupings from 1961 to the most recent year available. Data is sub-categorized in many aspects related to food and agriculture, from production and inputs, to greenhouse gas emissions and agri-environmental indicators.	FAO
WDI	The World Development Indicators (WDI) is a compilation of relevant, high-quality, and internationally comparable statistics about global development and the fight against poverty. The database contains 1,600 time series indicators for 217 economies and more than 40 country groups, with data for many indicators going back more than 50 years.	World Bank
SDG Indicator database	The platform that provides access to data compiled through the United Nations (UN) System in preparation for the Secretary-General's annual report on "Progress towards the Sustainable Development Goals (SDGs)", covering all available goals and targets.	UN
WEO, IMF Data	The World Economic Outlook (WEO) database, from the International Monetary Fund (IMF) contains selected macroeconomic data series from the statistical appendix of the World Economic Outlook report, which presents the IMF staff's analysis and projections of economic developments at the global level, in major country groups and in many individual countries.	IMF
ILOSTAT	The database of international standards relevant and timely labour statistic for better measurement of labour issues and enhanced international comparability, from the International Labour Organization (ILO).	ILO
AQUASTAT	AQUASTAT is the FAO global information system on water resources and agricultural water management. It collects, analyses and provides free access to over 180 variables and indicators by country from 1960.	FAO
CAIT	Climate Analysis Indicator Tool (CAIT), from the World Resources Institute (WRI) data platform is designed to empower policymakers, researchers, media and other stakeholders with the climate data, visualizations and resources they need to gather insights on national and global progress on climate change.	WRI
GHO	The Global Health Observatory (GHO), from the World Health Organization (WHO), is the gateway to health-related statistics for more than 1,000 indicators for its 194 Member States	WHO
ERS Data	Specifically, we explored the International Agricultural Productivity data product, from the United States Department of Agriculture (USDA). This data product from the Economic Research Service (ERS) provides agricultural output, inputs, and total factor productivity (TFP) indexes across the countries and regions of the world in a consistent, comparable way, for 1961-2016.	USDA
IFASTAT	IFASTAT is the world’s leading source of fertilizer and raw materials statistics. It provides access to15 years of global production, trade and supply data; and 45 years of plant nutrient consumption detailed data. Enables in-depth market outlooks; and factsheets, searchable by country, region and product.	IFA
GHDx	The world’s most comprehensive catalogue of surveys, censuses, vital statistics, and other health-related data. The GHDx is a place where information about data from those different places and providers is brought together, discussed, and featured in the context of health and demographic research. In addition, the GHDx raises awareness about different groups collecting data worldwide	IHME
NFA	The National Footprint Accounts (NFA) are an annual production from Global Footprint Network (GFN). Each year, this platform combines and synthesize over 30 datasets to calculate the Ecological Footprint and biocapacity of countries across the world in over 50 years.	GFN

Supplementary Table 4.3 – Main characteristics of metrics used in this study: duration, unit, and source

Metric	Duration	Unit	Source
Structure metrics			
Agricultural area	from 1961 to 2015	1000 ha and % of total land	FAOSTAT
Fertilizer use	from 1961 to 2015	Tonnes	FAOSTAT
Synthetic fertilizer use	from 1961 to 2014	Metric tonnes of nutrients	IFASTAT
Pesticide use	from 1990 to 2014	Tonnes	FAOSTAT
Agricultural employment	from 1991 to 2018	% of total employment	ILOSTAT
Agricultural water withdrawal	from 1965 to 2017 (5-years intervals)	10^9 m^3 and % of total water withdrawal	AQUASTAT
Agricultural water withdrawal from renewable water resources	from 1965 to 2017 (5-years intervals)	% of renewable resources	AQUASTAT
Gross Agricultural Output	from 1961 to 2015	constant US$ (year 2004-2006)	FAOSTAT
Gross Agricultural Value	from 1991 to 2016	current US$	FAOSTAT
Agricultural Total Factor Productivity	from 1961 to 2014	reference year of 1991 = 100	USDA
Agricultural Value Added	from 1960 to 2018	current US$ and % of GDP	WDI
Agricultural value added per worker	from 1970 to 2015	constant US$ (year 2005)	FAOSTAT
Agricultural Orientation Index	from 2001 to 2017	ratio	SDG Indicator database
Central government expenditure in agriculture, forestry, and fishing	from 2001 to 2017	current US$ and % of total government expenditure	FAOSTAT and IMF
Food imports	from 1962 to 2016	current US$	UNSD
Food exports	from 1961 to 2015	current US$	UNSD
Food imports-to-exports ratio	from 1961 to 2015	ratio	UNSD
Consumer Food Price, Food	from 2000 to 2018	reference year of 2010 = 100	FAOSTAT and IMF
Producer Food Price, Agriculture	from 1991 to 2017	reference year of 2004-2006 = 100	FAOSTAT
Domestic Food Price	from 2000 to 2014	Ratio	FAOSTAT
Domestic Food Price Volatility	from 2000 to 2014	average of standard deviations (previous 8 months)	FAOSTAT
Outcome metrics			
Per capita Food Supply Variability	from 2000 to 2016	kcal/capita/day	FAOSTAT
Forest area	from 1990 to 2015	1000 ha and % of total land	FAOSTAT
Red List Index	from 2000 to 2018	ratio	SDG Indicator database
Undernourishment	from 2000 to 2017	% of total population	WDI and FAO
Obesity	from 1975 to 2016	% of total population	GHO
Agricultural GHGE	from 1990 to 2014	$MtCO_2eq$, $MtCH_4$, and MtN_2O	CAIT
Land-Use Change and Forestry GHGE	from 1990 to 2014	$MtCO_2eq$, $MtCO_2$, $MtCH_4$, and MtN_2O	CAIT
Agriculture, Land-Use Change and Forestry GHGE	from 1990 to 2014	$MtCO_2eq$, $MtCO_2$, $MtCH_4$, and MtN_2O	CAIT
Ecological Footprint of Consumption	from 1961 to 2016	Global hectares (gha)	NFA
Socio-economic metrics			

Population Growth	from 1960 to 2018	people and people per sq. km of area	WDI and UNSD
GDP Per Capita	from 1980 to 2018	current US$ per capita	IMF Data
Gini index	from 1979 to 2017	0 to 1, continuous range	WDI
Socio-Demographic Index	from 1950 to 2017	0 to 1, continuous range	GHDx
Income category	from 1987 to 2018	Categorical	WDI
Human Development Index (HDI)	from 1990 to 2018	0 to 1, continuous range	UNDP

Abbreviations: Data repository from the Food and Agriculture Organization of the United Nations (FAOSTAT); Data repository from the International Fertilizer Association (IFASTAT); Data repository from the International Labour Organization (ILOSTAT); Data repository of water management from the Food and Agriculture Organization of the United Nations (AQUASTAT); United States Department of Agriculture (USDA); World Development Indicators (WDI), from the World Bank; Data repository for the United Nations Sustainable Development Goals (SDG Indicator database); Data repository from the International Monetary Fund (IMF and IMF Data); The United Nations Statistics Division (UNSD); Global Health Observatory (GHO), from the World Health Organization; Climate Analysis Indicator Tool (CAIT), from the World Resource Institute; National Footprint and Biocapacity Accounts (NFA), from the Global Footprint Network; Global Health Data Exchange (GHDx), from the Institute of Health Metrics and Evaluation; the United Nations Development Programme (UNDP).

A4.3 Data preparation

At this stage, all metrics were ordered chronologically and alphabetically, NA objects were removed, country names were uniformized for potentially different spelling and/or abbreviations from distinct datasets (e.g., ‘Democratic Republic of Congo’ and ‘Congo, Dr’), and units were controlled for appropriate comparison of the same measurement (e.g., area in 1,000 hectares or % of total land area, and weight in tonnes or kilogram per hectare).

The code for data standardization by ‘country’, ‘year’, and ‘value’ is available for all metrics acquired in this study, grouped as structure or outcome metrics. Hierarchical allocation of metrics followed the format of individual variables, derived variables, and aggregate indicators. Individual variables expressed the quantification of metrics in simple standards (e.g., ha or kg). Derived variables resulted from the combination of two or more individual variables to devise a new measure (e.g., kg/ha or % of agricultural employment). Sometimes additional information was required to derive variables (e.g., conversion of individual greenhouse gas emissions to total CO2 equivalents). Aggregate indicators were calculated as a product of two or more derived variables and assesses them against a particular function (e.g., Agricultural Total Factor Productivity or Red List Index).

The initial filter analysis simply removed the countries which did not meet the initial criteria for global comparison (data for ≥100 countries and ≥10 years of observations), after the data standardization. The code for the refined filter analysis (analysis of best fit) disaggregated the remaining metrics in standardized windows of time, starting from pre-stablished minimum year of 1961 and ending at the maximum year of 2015. The standardized windows of time were: from 1961 to 2015; from 1980 to 2015; from 1990 to 2015; from 1995 to 2015; from 2000 to 2015; from 2005 to 2015; from 1961 to 2005;

from 1980 to 2005; from 1990 to 2005; from 1995 to 2005; and from 2000 to 2005. In each window of time assessed (n = 11, per metric), filters of best fit defined at 70%, 80%, and 90% of the respective maximum duration calculated the number of countries with sufficient observations for these cut-points. An example of a table generated by the refined filter analysis for the metric of Agricultural area is shown in the Supplementary Table 4.4, whilst a complete description of the refined filter analysis is available in the Supplementary Table 4.5. Filter of best fit to assess the final number of countries that entered the trend analysis was established at 80% due to the small difference in the number of countries found in comparison with the 70% and considerable superior 80% filters for each window of time.

Supplementary Table 4.4 – Filter of best fit for the metric Agricultural area.

Filter	**≥ 90% of possible duration**	**≥ 80% of possible duration**	**≥ 70% of possible duration**
(start and end year)	(no. of countries)	(no. of countries)	(no. of countries)
1961 – 2015	192	192	193
1980 – 2015	191	192	192
1990 – 2015	212	217	217
1995 – 2015	216	216	219
2000 – 2015	218	218	218
2005 – 2015	220	220	220
1961 – 2005	192	193	195
1980 – 2005	192	192	193
1990 – 2005	195	218	218
1995 – 2005	218	218	218
2000 – 2005	220	220	220

Supplementary Table 4.5 – Descriptive results of structure, outcome, and socioeconomic metrics after the data preparation stage.

Metric	**Baseline start year**	**Baseline final year**	**Initial (no. of countries)**	**Filter, 90% (no. of countries)**	**Filter, 80% (no. of countries)**
Structure metrics					
Agriculture area	1961	2015	226	216	216
Synthetic fertilizer use	1961	2014	170	170	170
Pesticide use	1990	2015	109	68	86
Agricultural employment	1991	2018	186	186	186
Gross Agricultural Output	1961	2014	212	207	208
Agricultural Total Factor Productivity	1961	2014	170	170	170
Food import	1962	2016	179	155	165
Food export	1962	2016	177	155	165
Consumer Price Index, Food	2000	2018	133	64	71
Producer Price Index, Agriculture	1991	2017	149	140	145
Domestic Food Price	2000	2014	145	0	0
Outcome metrics					
Forest area	1990	2015	223	216	216
Red List Index	2000	2019	194	195	195
Ecological Footprint of Consumption	1961	2016	185	175	177
Undernourishment	2000	2017	165	0	163
Obesity	1975	2016	189	189	189
Agricultural GHGE	1990	2014	191	191	191
Land-use change and Forestry GHGE	1990	2014	191	191	191
AFOLU GHGE	1990	2014	191	191	191
Per capita food supply variability	2000	2016	171	0	0
Socioeconomic metrics					
GDP per capita	1980	2018	194	177	180
Income category	1987	2018	194	180	180
Human Development Index (HDI)	1990	2018	135	135	135

The filter of best fit analysis was stipulated at 80% of maximum duration from 1995 to 2015. Abbreviations: GHGE – Greenhouse gases emissions; AFOLU – Agriculture, Land-Use Change and Forestry.

A4.4. Data analysis

Following data acquisition and preparation, our data analysis was conducted in four steps: a) trend analysis of structure and outcome metrics; b) cluster algorithm, c) significance testing; and c) five-year intervals analysis.

4.4.a Trend analysis

The trend analysis for the structure metrics was formulated in Script 3, whilst the same equations to measure the longitudinal pathway of outcome metrics were calculated in Script 4. The trend analysis is described by the adjusted Compound Annual Change Rate (CACR) of these metrics.

4.4.b Cluster algorithm

Script 5 aggregates countries into groups (assigned by the cluster analysis) based on the adapted CACR in key food systems metrics: agricultural area, synthetic fertilizer use, agricultural employment, gross agricultural output, and Agricultural Total Factor Productivity.

4.4.c Significance testing

Following the application of the cluster algorithm, statistical difference for the adjusted CACR of all metrics was assessed across groups by ANOVA, and Tukey’s honest significance test was applied to identify differences amongst specific groups.

4.4.d Five-year intervals analysis

The five-year intervals analysis is available in Script 6. The trend analysis for the five-year intervals (from 1995 to 2000; from 2000 to 2005; from 2005 to 2010; and from 2010 to 2015) was calculated by the conventional equation of CACR, for each time period:

$$CACR = \left(\frac{End\ value}{Start\ value}\right)^{\left(\frac{1}{End\ value\ (Year) - Start\ value\ (Year)}\right)} - 1\ \times 100$$

A4.5 Metadata

Metadata is composed by 36 metrics, divided into three main groups: food systems structure metrics (n=21), outcome metrics (n=9), and socio-economic metrics (n=6). The structure metrics are subdivided into input (n=7), output (n=2), productivity (n=1), and economic metrics (n= 11), whilst the outcome metrics reveal the impacts on malnutrition (n=3), biosphere integrity & land-system change (n=3), and greenhouse gases emissions (n=3). Other metrics include generic social-economic conditions (n=6) of population growth, GDP per capita, Gini Index, Socio-demographic Index, income category, and Human Development Index (HDI).

1. Structural:

1.1 Input:

1.1.1 Agricultural area:

- Link: http://www.fao.org/faostat/en/#data/RL
- Description: agricultural area, this category is the sum of areas under “Arable land”, “Permanent crops” and “Permanent pastures”, measured in 1,000 hectares.
- Source: FAOSTAT.
- Periodicity: annually, 1961 – 2015.
- Unit: 1000 ha and % of total land.

1.1.2 Fertilizer use, total:

- Link: http://www.fao.org/faostat/en/#data/RA
- Description: fertilizer products cover nitrogenous, potash, and phosphate fertilizers (including ground rock phosphate). Traditional nutrients--animal and plant manures--are not included. For the purpose of data dissemination, FAO has adopted the concept of a calendar year (January to December). Some countries compile fertilizer data on a calendar year basis, while others are on a split-year basis. Datasets subdivided into: 1) all

fertilizers used from 1961 to 2002; and 2) total consumption from 2002 to present (data calculated as kg/ha of arable land * ha arable land / 1,000).

- Source: FAOSTAT.
- Periodicity: annually, 1961 – 2002; Annually, 2002 – 2015.
- Unit: tonnes.

1.1.3 Synthetic fertilizer use:

- Link: https://www.ifastat.org/databases/plant-nutrition
- Description: metric tonnes of N, P2O5, K2O fertilizer consumption. Data on N, P2O5, and K2O fertilizer consumption are from the International Fertilizer Association (IFA) where available, and otherwise from FAO (FAO data are used mainly for small countries).
- Source: IFASTAT.
- Periodicity: annually, 1961 – 2014.
- Unit: metric tonnes of nutrients.

1.1.4 Pesticide use, total:

- Link: http://www.fao.org/faostat/en/#data/RP
- Description: total pesticides, covering insecticides, fungicides and bactericides (including seed treatments), herbicides, plant growth regulators, rodenticides, mineral oils, disinfectants and others.
- Source: FAOSTAT.
- Periodicity: annually, 1990 – 2014.
- Unit: tonnes of active ingredients.

1.1.5 Agricultural water withdrawal:

- Link: http://www.fao.org/nr/water/aquastat/data/query/results.html
- Description: annual quantity of self-supplied water withdrawn for irrigation, livestock

and aquaculture purposes. It can include water from primary renewable and secondary freshwater resources, as well as water from over-abstraction of renewable groundwater or withdrawal from fossil groundwater, direct use of agricultural drainage water, direct use of (treated) wastewater, and desalinated water. Water for the dairy and meat industries and industrial processing of harvested agricultural products is included under industrial water withdrawal.

- Source: AQUASTAT.
- Periodicity: intervals of five years, 1965 – 2017.
- Unit: 109 m3 and % of total water withdrawal.

1.1.6 Agricultural water withdrawal from renewable water resources:

- Link: http://www.fao.org/nr/water/aquastat/data/query/results.html
- Description: water withdrawn for irrigation in a given year, expressed in percent of the total renewable water resources (TRWR). This parameter is an indication of the pressure on the renewable water resources caused by irrigation. Note: While freshwater withdrawal as % of total renewable water resources refers to withdrawal of primary and secondary surface water and groundwater, agricultural water withdrawal also includes non-conventional sources of water (such as direct use of wastewater and agricultural drainage water, desalinated water). That's why in some countries agricultural water withdrawal as % of total renewable water resources can be higher than freshwater withdrawal as % of total renewable water resources. Calculation Criteria: [Agricultural water withdrawal as % of total renewable water resources] = 100*[Agricultural water withdrawal]/[Total renewable water resources].
- Source: AQUASTAT.
- Periodicity: intervals of five years, 1965 – 2017.
- Unit: % of renewable resources.

1.1.7 Agricultural employment:

- Link: https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?end=2018&locations=AF-BR&start=1991&view=chart
- Description: employment is defined as persons of working age who were engaged in any activity to produce goods or provide services for pay or profit, whether at work during the reference period or not at work due to temporary absence from a job, or to working-time arrangement. The agriculture sector consists of activities in agriculture, hunting, forestry and fishing, in accordance with division 1 (ISIC 2) or categories A-B (ISIC 3) or category A (ISIC 4).
- Source: ILOSTAT.
- Periodicity: annually, 1991 – 2018.
- Unit: % of total employment.

1.2 Output:

1.2.1 Gross Agricultural Output (GAO):

- Link: http://www.fao.org/faostat/en/#data/QV
- Description: the FAO indices of agricultural production show the relative level of the aggregate volume of agricultural production for each year in comparison with the base period 2004-2006. Constant price series can be used to show how the quantity or volume of products has changed, and are often referred to as volume measures. They are based on the sum of price-weighted quantities of different agricultural commodities produced after deductions of quantities used as seed and feed weighted in a similar manner. The resulting aggregate represents, therefore, disposable production for any use except as seed and feed. Production quantities of each commodity are weighted by 2004-2006 average international commodity prices and summed for each year. To obtain the index, the aggregate for a given year is divided by the average aggregate for the base period 2004-2006. Since the FAO indices are based on the concept of agriculture as a single

enterprise, amounts of seed and feed are subtracted from the production data to avoid double counting them, once in the production data and once with the crops or livestock produced from them. Deductions for seed (in the case of eggs, for hatching) and for livestock and poultry feed apply to both domestically produced and imported commodities. They cover only primary agricultural products destined to animal feed (e.g. maize, potatoes, milk, etc.). Processed and semi-processed feed items such as bran, oilcakes, meals and molasses have been completely excluded from the calculations at all stages. It should be noted that when calculating indices of agricultural, food and non-food production, all intermediate primary inputs of agricultural origin are deducted. However, for indices of any other commodity group, only inputs originating from within the same group are deducted; thus, only seed is removed from the group "crops" and from all crop subgroups, such as cereals, oil crops, etc.; and both feed and seed originating from within the livestock sector (e.g. milk feed, hatching eggs) are removed from the group "livestock products". For the main two livestock subgroups, namely, meat and milk, only feed originating from the respective subgroup is removed. Practically all products are covered, with the main exception of fodder crops. The category of food production includes commodities that are considered edible and that contain nutrients. Accordingly, coffee and tea are excluded along with inedible commodities because, although edible, they have practically no nutritive value. Indices for meat production are computed based on data for production from indigenous animals, which takes account of the meat equivalent of exported live animals but excludes the meat equivalent of imported live animals. For index purposes, annual changes in livestock and poultry numbers or in their average live weight are not taken into account. The indices are calculated from production data presented on a calendar year basis. The FAO indices may differ from those produced by the countries themselves because of differences in concepts of production, coverage, weights, time reference of data and methods of calculation.

- Source: FAOSTAT.
- Periodicity: annually, 1961 – 2015.

- Unit: reference year of 2004-2006 = 100 (constant International dollars, Int. $).

1.2.2 Gross Agricultural Value (GAV):

- Link: http://www.fao.org/faostat/en/#data/QV
- Description: the current value of production measures value in the prices relating to the period being measured. Thus, it represents the market value of food and agricultural products at the time they were produced. Knowing this figure is helpful in understanding exactly what was happening within a given economy at that point in time. Often, this information can help explain economic trends that emerged in later periods and why they took place.
- Source: FAOSTAT.
- Periodicity: annually, 1991 – 2016.
- Unity: current US$ (current International dollars, Int. $).

1.3 Productivity (Input and Output):

1.3.1 Agricultural Total Factor Productivity (TFP) Index:

- Link: https://www.ers.usda.gov/data-products/international-agricultural-productivity/
- Description: TFP is an indicator of how efficiently agricultural land, labour, capital, and materials (agricultural inputs) are used to produce a country’s crops and livestock (agricultural output)—it is calculated as the ratio of total agricultural output to total production inputs. Output is FAO gross agricultural output (GAO). Input growth is the weighted-average growth in quality-adjusted land, labour, machinery power, livestock capital, synthetic NPK fertilizers, and animal feed, where weights are input (factor) cost shares.
- Source: USDA, Economic Research Service.
- Periodicity: annually, 1961 – 2014.
- Unit: reference year of 1991 = 100.

1.4 Economic metrics: Policy, trade and price.

1.4.1 Food imports:

- Link: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#
- Description: food comprises the commodities in SITC sections 0 (food and live animals), 1 (beverages and tobacco), and 4 (animal and vegetable oils and fats) and SITC division 22 (oil seeds, oil nuts, and oil kernels). Previous editions contained data based on the SITC revision 1. Data for earlier years in previous editions may differ because of the change in methodology. Concordance tables are available to convert data reported in one system to another. Merchandise import shares may not sum to 100 percent because of unclassified trade. Data calculated as Food import (% of merchandise) * merchandise import / 100.
- Source: World Bank staff estimates through the WITS platform from the Comtrade database maintained by the United Nations Statistics Division. Standard International Trade Classification available at: https://unctadstat.unctad.org/EN/Classifications/DimSitcRev3Products_Official_Hierarchy.pdf
- Periodicity: annually, 1962 – 2016.
- Unit: current US$.

1.4.2 Food exports:

- Link: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#
- Description: food comprises the commodities in SITC sections 0 (food and live animals), 1 (beverages and tobacco), and 4 (animal and vegetable oils and fats) and SITC division 22 (oil seeds, oil nuts, and oil kernels). Previous editions contained data based on the SITC revision 1. Data for earlier years in previous editions may differ because of the

change in methodology. Concordance tables are available to convert data reported in one system to another. Merchandise import shares may not sum to 100 percent because of unclassified trade. Data calculated as Food export (% of merchandise) * merchandise export / 100.

- Source: World Bank staff estimates through the WITS platform from the Comtrade database maintained by the United Nations Statistics Division.
- Periodicity: annually, 1962 – 2016.
- Unit: current US$.

1.4.3 Food imports-to-exports ratio:

- Link: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators#
- Description: proportion of the amount of food imported by the amount of food exported. Same classification of the metrics ‘Food imports’ and ‘Food exports’ are applied. Data calculated as food imports / food exports.
- Source: World Bank staff estimates through the WITS platform from the Comtrade database maintained by the United Nations Statistics Division.
- Periodicity: annually, 1962 – 2016.
- Unit: ratio.

1.4.4 Agriculture value added:

- Link: https://databank.worldbank.org/source/world-development-indicators
- Description: agriculture value added is the net output of the agriculture sector, including forestry, hunting and fishing, and cultivation of crops and livestock production, after adding up all outputs and subtracting intermediate inputs. Deductions for depreciation of fabricated assets and depletion and degradation of natural resources are not included in the calculation.
- Source: World Development Indicators, World Bank.

- Periodicity: annually, 1960 – 2018.
- Unit: current US$ and % of GDP.

1.4.5 Agricultural value added per worker:

- Link: http://www.fao.org/faostat/en/#data/OE
- Description: this indicator provides information on the output of the agricultural sector (agriculture forestry and fishery) by worker engaged in that sector. It is a measure of average productivity. Value added represents the contribution of labour and capital to the production process.
- Source: FAOSTAT
- Periodicity: annually, 1970 – 2015.
- Unit: reference year of 2005 = 100 (constant International dollars, Int. $).

1.4.6 Central government expenditure in agriculture, forestry, and fishing:

- Link: http://www.fao.org/faostat/en/#data/IG
- Description: the Statistics Division of FAO collects annually data on Government Expenditure on Agriculture through a questionnaire, which was developed in partnership with the International Monetary Fund. The IMF is the responsible institution for the Government Finance Statistics (GFS) methodology and annually collects GFS data, including Expenditure by Functions of Government (COFOG). The Classification of the Functions of Government (COFOG) is an international classification developed by Organisation for Economic Co-operation and Development (OECD) and published by the United Nations Statistical Division (UNSD), with the aim of categorise governments' functions according to their purposes. The FAO questionnaire aligns with Table 7 of the IMF GFS questionnaire, replicates the relevant aggregates and drills down to request additional detail related to Agriculture. The FAO dataset consists of a time series, from 2001 onwards, of Total Government Expenditure and expenditure in: Economic affairs; Agriculture, Forestry, Fishing and Hunting, along with its three disaggregated subsectors

of Agriculture, Forestry and Fishing; and Environmental Protection. In addition, expenditure in each detailed function are further disaggregated into Recurrent and Capital expenditure. Though the goal is to have complete and consistent coverage for all countries, different stages of implementation of the GFS methodology and COFOG classification, and differences in the data collection and reporting at country level creates some challenges in providing a complete and consistent global dataset.

- Source: FAOSTAT and IMF.
- Periodicity: annually, 2001 – 2017.
- Unit: current US$ and % of total government expenditure.

1.4.7 Agricultural Orientation Index (AOI):

- Link: https://unstats.un.org/sdgs/indicators/database/
- Description: the Agriculture Orientation Index (AOI) for Government Expenditures is defined as the Agriculture share of Government Expenditure, divided by the Agriculture value added share of GDP, where Agriculture refers to the agriculture, forestry, fishing and hunting sector.
- Source: SDG Indicators database.
- Periodicity: annually, 2001 – 2017.
- Unit: ratio.

1.4.8 Consumer Food Price (CPI), Food:

- Link: http://www.fao.org/faostat/en/#data/CP
- Description: these indices measure the price change between the current and reference periods of the average food in a basket of goods and services purchased by households. The CPI, all items is typically used to measure and monitor inflation, set monetary policy targets, index social benefits such as pensions and unemployment benefits, and to escalate thresholds and credits in the income tax systems and wages in public and private wage contracts.

- Source: FAOSTAT (CPI total is from IMF Data).
- Periodicity: annually, 2000 – 2018.
- Unit: reference year of 2010 = 100.

1.4.9 Producer Food Price (PPI), Agriculture:

- Link: http://www.fao.org/faostat/en/#data/PI
- Description: measures the average annual change over time in the selling prices received by farmers (prices at the farm-gate or at the first point of sale). Annual data are provided for over 80 countries. The three categories of producer price indices available in FAOSTAT comprise: Single-item price indices, Commodity group indices and the Agriculture producer price index.
- Source: FAOSTAT.
- Periodicity: annually, 1991 – 2017.
- Unit: reference of 2004-2006 = 100.

1.4.10 Domestic Food Price (index):

- Link: https://landportal.org/book/indicators/indfaofsec1
- Description: domestic food price level index is an important indicator for global monitoring of food security because it compares the relative price of food across countries and over time. The Domestic Food Price Level Index is calculated by dividing the Food Purchasing Power Parity (FPPP) by the General PPP, thus providing an index of the price of food in the country relative to the price of the generic consumption basket. Data are available for 2005 from the ICP Program. It is then extended to other years by adjusting both numerator and denominator using the relative changes in Food CPI and General CPI as provided by ILO. It allows comparison of the relative price of food across countries and over time.
- Source: FAOSTAT.
- Periodicity: annually, 2000 – 2014.

- Unit: ratio.

1.4.11 Domestic Food Price volatility (index):

- Link: https://landportal.org/book/indicator/fao-21029-6125
- Description: the domestic food price volatility index measures the variability in the relative price of food in a country. The indicator is calculated from the monthly domestic food price level index (using monthly consumer and general food price indices) and purchasing power parity data from the International Comparison Program conducted by the World Bank. Month-to-month growth rates are calculated, and the standard deviation of these growth rates are calculated over the previous 8 months (8-months rolling standard deviation). The average of these standard deviations is then computed to obtain an annual volatility indicator.
- Source: FAOSTAT.
- Periodicity: annually, 2000 – 2014.
- Unit: average of standard deviations calculated over the previous 8 months.

2. Outcomes:

2.1 Malnutrition:

2.1.1 Prevalence of adult Obesity:

- Link: https://ourworldindata.org/obesity (Share of adults defined as obese, 2016)
- Description: prevalence of obesity is the percentage of adults (18+ years) whose Body Mass Index (BMI) is greater than or equal 30. BMI is a weight-to-height ratio. The formula for determining BMI is weight (kg) / [height (m)]2.
- Source: Global Health Observatory (GHO), World Health Organization
- Periodicity: annually, 1975 – 2016.
- Unit: % of total population.

2.1.2 Prevalence of Undernourishment:

- Link: https://unstats.un.org/sdgs/indicators/database/?indicator=2.1.1
- Description: This is the main FAO hunger indicator. It measures the share of the population that has a caloric intake which is insufficient to meet the minimum energy requirements necessary for a given individual. Data showing as 5 may signify a prevalence of undernourishment below 5%. Regional aggregations are based on World Bank regions and exclude high-income countries. They may therefore differ from UN FAO regional figures.
- Source: the share of people who are undernourished was derived from the World Bank, World Development Indicators and the UN FAO State of Food Insecurity 2017. Global figures from 2005 onwards are from the UN SOFI (2018) report. Important note: prevalence of undernourishment does not include some high-income countries (below 5% of undernourishment).
- Periodicity: annually, from 1991 – 2017.
- Unit: % of total population.

2.1.3 Per capita food supply variability:

- Link: http://www.fao.org/faostat/en/#data/FS
- Description: per capita food supply variability corresponds to the variability of the "food supply in kcal/caput/day" as disseminated in FAOSTAT. The per capita food supply variability compares the variations of the food supply across countries and time.
- Source: FAOSTAT.
- Periodicity: annually, 2000 – 2016.
- Unit: kilocalories per capita per day (kcal/capita/day).

2.2 Greenhouse Gases Emissions:

2.2.1 Agricultural greenhouse gases emissions:

- Link: https://www.climatewatchdata.org/ghg-emissions?sectors=512%2C514
- Description: the CAIT Agriculture sector includes CH4 and N2O emission from the

following activities, drawing on data from the Statistic Division of the Food and Agriculture Organization of the United States (FAOSTAT): CH4 from Enteric Fermentation (Livestock); CH4 and N2O from Livestock Manure Management CH4 from Rice Cultivation; N2O from Agricultural Soils (Synthetic Fertilizers, Manure Applied to Soils, Manure Applied to Pasture, Crop Residues, and Cultivation of Organic Soils); CH4 and N2O from Other Agricultural Sources (Burning – Crop Residues, Burning – Savanna).This sector is compiled in CAIT so as to best match IPCC Source/Sink Category 4 (Agriculture) (IPCC, 1996b). This category does not include CO2 emissions from fossil fuels associated with agricultural activities. Details available at: http://cait.wri.org/docs/CAIT2.0_CountryGHG_Methods.pdf

- Source: CAIT, World Resources Institute.
- Periodicity: annually, 1990 – 2014.
- Unit: Mt (Megatons) of total CO2eq, CH4, and N2O.

2.2.2 Land-Use Change and Forestry greenhouse gases emissions:

- Link: https://www.climatewatchdata.org/ghg-emissions?sectors=512%2C514
- Description: GHG emissions and removals from Forestry and Other Land Use (FOLU) sectors consist of CO2 and non-CO2 gases (methane, CH4, and nitrous oxide, N2O), produced by aerobic and anaerobic processes, e.g. combustion and decay, and by harvesting associated with land management activities. Land Use Total contains total emissions and removals for each relevant greenhouse gas (CO2, CH4, N2O), expressed in CO2equivalents, aggregated for the following sub-domains: Forest Land (CO2, CH4, N2O); Cropland (CO2), Grassland (CO2); Burning – Biomass (CO2, CH4, N2O). Details available at: http://cait.wri.org/docs/CAIT2.0_CountryGHG_Methods.pdf
- Source: CAIT, World Resources Institute.
- Periodicity: annually, 1990 – 2014.
- Unit: Mt (Megatons) of total CO2eq, CO2, CH4, and N2O.

2.2.3 Agricultural, Land-Use Change, and Forestry (AFOLU) greenhouse gases emissions:

- Link: https://www.climatewatchdata.org/ghg-emissions?sectors=512%2C514
- Description: the sector representing the combination of Agriculture, Forestry, and Other Land Use (AFOLU). The AFOLU sector is responsible for just under a quarter (~10–12 GtCO2eq/yr) of anthropogenic GHG emissions mainly from deforestation and agricultural emissions from livestock, soil and nutrient management. More details at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf
- Source: CAIT, World Resources Institute.
- Periodicity: annually, 1990 – 2014.
- Unit: Mt (Megatons) of total CO2eq, CO2, CH4, and N2O.

2.3 Biosphere integrity & Land-system change:

2.3.1 Forest land:

- Link: http://www.fao.org/faostat/en/#data/RL
- Description: forest area is the land spanning more than 0.5 hectares with trees higher than 5 metres and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use. Forest is determined both by the presence of trees and the absence of other predominant land uses. The trees should be able to reach a minimum height of 5 metres (m) in situ. Areas under reforestation that have not yet reached but are expected to reach a canopy cover of 10 percent and a tree height of 5 m are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate. Includes: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m; plantations

primarily used for forestry or protective purposes, such as: rubber-wood plantations and cork, oak stands. Excludes: tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens.

- Source: FAOSTAT.
- Periodicity: annually, 1990 – 2015.
- Unit: 1000 ha and % of total land.

2.3.2 Red List Index:

- Link: https://unstats.un.org/sdgs/indicators/database/
- Description: the Red List Index measures change in aggregate extinction risk across groups of species (for animals and plants). It is based on genuine changes in the number of species in each category of extinction risk on The IUCN Red List of Threatened Species (IUCN 2015) is expressed as changes in an index ranging from 0 to 1. The Red List Index is calculated at a point in time by first multiplying the number of species in each Red List Category by a weight (ranging from 1 for ‘Near Threatened’ to 5 for ‘Extinct’ and ‘Extinct in the Wild’) and summing these values. This is then divided by a maximum threat score which is the total number of species multiplied by the weight assigned to the ‘Extinct’ category. This final value is subtracted from 1 to give the Red List Index value. Important note: total species assessed are increasing more than total species threatened, which might result in a false positive result if trends are analysed. See Figure 1 at: https://www.iucnredlist.org/resources/summary-statistics. In addition, there is substantial inconsistency between species assessments. See Figure 1 at: https://www.iucnredlist.org/assessment/red-list-index. Full details available for download at: Metadata is available at: https://unstats.un.org/sdgs/metadata/files/Metadata-15-05-01.pdf
- Source: SDG Indicators database.
- Periodicity: annually, 2000 – 2018.

- Unit: 0 to 1, continuous range.

2.3.3 Ecological Footprint of Consumption (EFC):

- Link: http://data.footprintnetwork.org/?_ga=2.231131615.1142436365.1572453106-502500962.1572453106#/
- Description: the most commonly reported type of Ecological Footprint, it is defined as the area used to support a defined population's consumption. The consumption Footprint (in gha) includes the area needed to produce the materials consumed and the area needed to absorb the carbon dioxide emissions. The consumption Footprint of a nation is calculated in the National Footprint and Biocapacity Accounts as a nation's primary production Footprint plus the Footprint of imports minus the Footprint of exports, and is thus, strictly speaking, a Footprint of apparent consumption. The national average of per capita Consumption Footprint is equal to a country's Consumption Footprint divided by its population. Detailed methodology available at: https://www.mdpi.com/2079-9276/7/3/58
- Source: National Footprint and Biocapacity Accounts (NFA), Global Footprint Network.
- Periodicity: annually, 1961 – 2016.
- Unit: Global hectares (gha).

3. Socio-economic metrics:

3.1 Population growth:

- Link: https://databank.worldbank.org/source/world-development-indicators
- Description: number of people living in a particular country. Expressed as total population or population density (people per sq. km of area).
- Source: World Development Indicators, World Bank.
- Periodicity: annually, 1960 – 2018.
- Unit: people or people per sq. km of area.

Appendix 4

3.2 GDP per capita:

- Link: https://www.imf.org/external/pubs/ft/weo/2019/01/weodata/weoselco.aspx?g=2001&sg=All+countries
- Description: expressed as Nominal or Purchasing Power Parity (PPP). Nominal: GDP is expressed in current U.S. dollars per person. Data are derived by first converting GDP in national currency to U.S. dollars and then dividing it by total population. PPP: Data are derived by dividing GDP in PPP dollars by total population. These data form the basis for the country weights used to generate the World Economic Outlook country group composites for the domestic economy.
- Source: IMF Data.
- Periodicity: annually, 1980 – 2018.
- Unit: current US$ per capita.

3.3 Gini Index:

- Link: https://databank.worldbank.org/source/world-development-indicators
- Description: Gini index measures the extent to which the distribution of income (or, in some cases, consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients, starting with the poorest individual or household. The Gini index measures the area between the Lorenz curve and a hypothetical line of absolute equality, expressed as a percentage of the maximum area under the line. Thus, a Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality.
- Source: World Development Indicators, World Bank.
- Periodicity: annually, 1979 – 2017.
- Unit: 0 to 1, continuous range.

3.4 Socio-Demographic Index (SDI):

- Link: http://ghdx.healthdata.org/record/ihme-data/gbd-2017-socio-demographic-index-sdi-1950%E2%80%932017
- Description: composite indicator of development status strongly correlated with health outcomes. It is the geometric mean of 0 to 1 indices of total fertility rate under the age of 25 (TFU25), mean education for those ages 15 and older (EDU15+), and lag distributed income (LDI) per capita. As a composite, a location with an SDI of 0 would have a theoretical minimum level of development relevant to health, while a location with an SDI of 1 would have a theoretical maximum level. Details available at: http://ghdx.healthdata.org/sites/default/files/record-attached-files/IHME_GBD_2017_SDI_1950_2017_INFO_SHEET_Y2018M11D08_0.PDF
- Source: Global Health Data Exchange, IHME.
- Periodicity: annually, 1950 – 2017.
- Unit: 0 to 1, continuous range.

3.5 Income category:

- Link: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups
- Description: economies are currently divided into four income groups: low, lower-middle, upper-middle, and high, based on GNI per capita (in U.S. dollars, converted from local currency using the Atlas method). In calculating gross national income (GNI—formerly referred to as GNP) in U.S. dollars for certain operational and analytical purposes, the World Bank uses the Atlas conversion factor instead of simple exchange rates. The purpose of the Atlas conversion factor is to reduce the impact of exchange rate fluctuations in the cross-country comparison of national incomes. The Atlas conversion factor for any year is the average of a country's exchange rate for that year and its exchange rates for the two preceding years, adjusted for the difference between the rate

of inflation in the country and international inflation; the objective of the adjustment is to reduce any changes to the exchange rate caused by inflation. Income thresholds are updated annually at the beginning of the World Bank's fiscal year (i.e., July 1), with an adjustment for inflation. The current methodology for measuring inflation for this purpose is to use the change in a deflator (the “SDR deflator”).

- Source: World Development Indicators, World Bank.
- Periodicity: annually, 1987 – 2018.
- Unit: categorical (Low-income economies, Lower-middle-income economies, Upper-middle-income economies, and High-income economies).

3.6 Human Development Index (HDI):

- Link: http://hdr.undp.org/en/data#
- Description: the Human Development Index (HDI) is a summary measure of achievements in three key dimensions of human development: a long and healthy life, access to knowledge and a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions. The indicators used to calculate the three dimensions are: life expectancy (in years) for health; expected years of schooling (in years) and mean years of schooling (in years) for education; gross national income per capita (2011 PPP $) for standard of living. Human development categories are different by cut-off points for each group: 0.800 and above for very high human development; 0.700–0.799 for high human development, 0.550–0.699 for medium human development, and 0.550–0.699 for low human development.
- Source: the United Nations Development Programme (UNDP).
- Periodicity: Annually, 1990 – 2018.
- Unit: 0 to 1 (continuous range) or categorical (Very high human development, High human development, Medium human development, and Low human development).

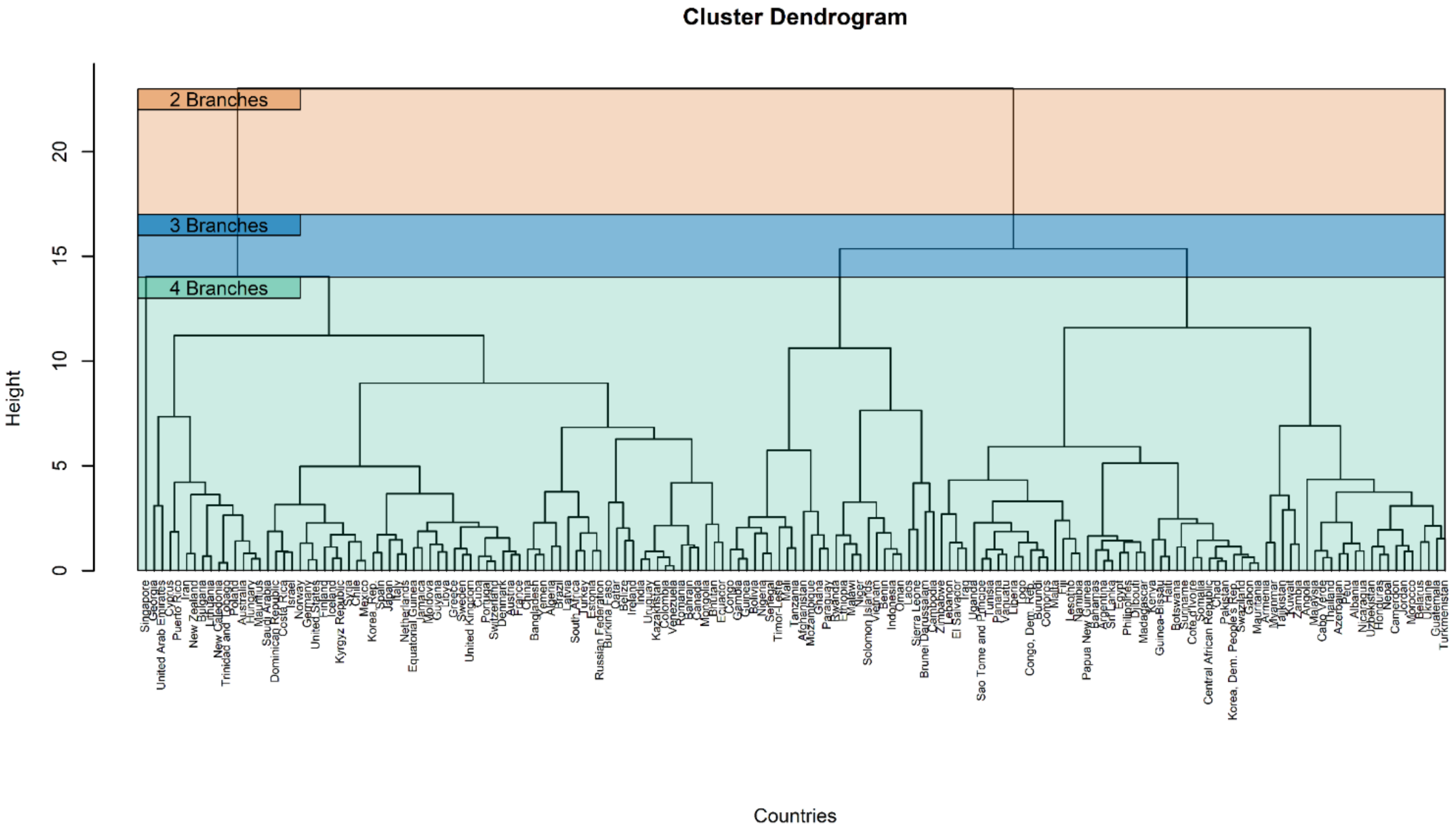
Supplementary results to chapter 4

A4.6 Descriptive results and cluster algorithm output

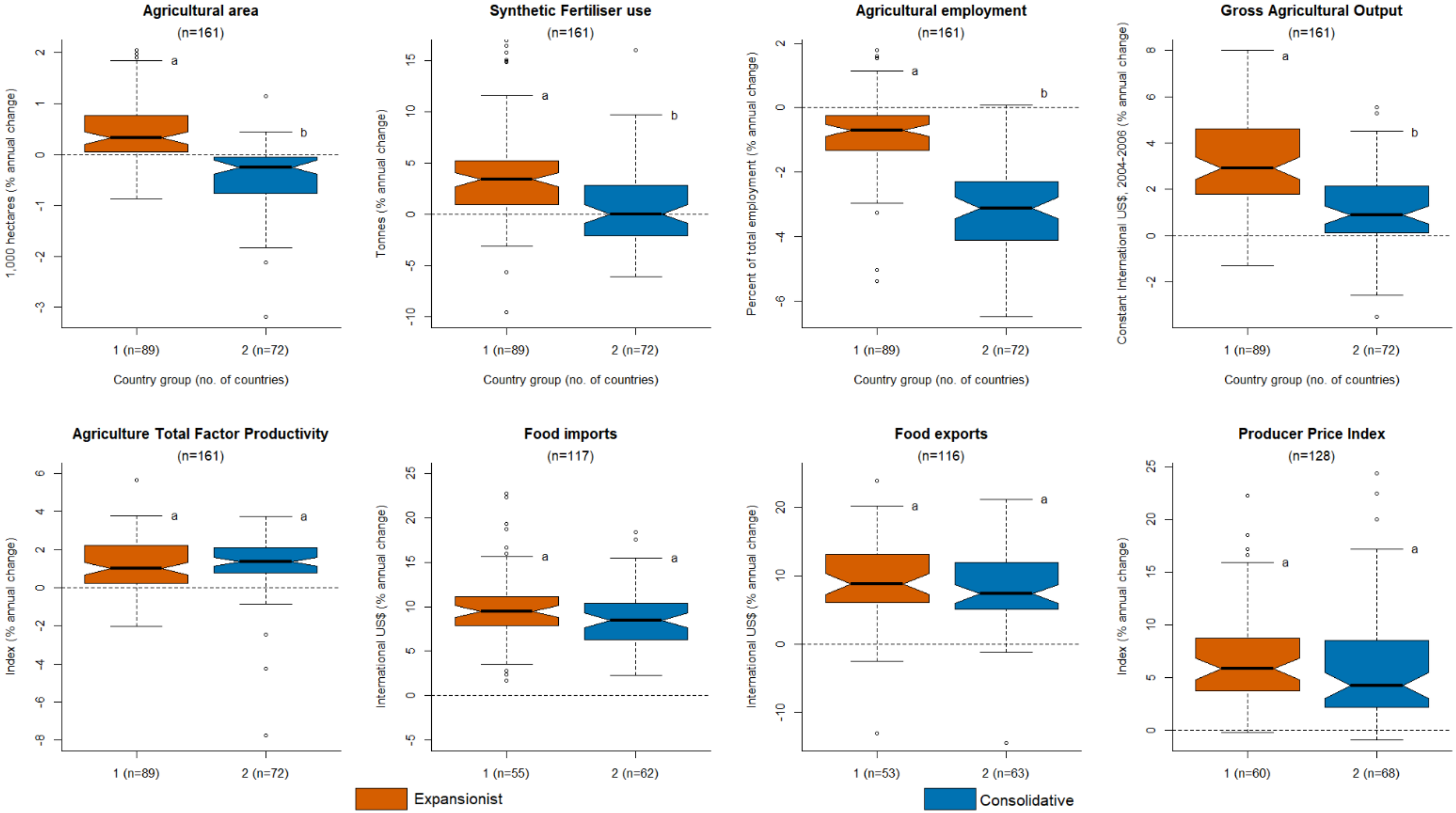
Our aggregated dataset was initially composed by a total of 36 comprehensive food systems metrics – 6 of these were socio-economic indicators and 30 expressed multiple structure and outcome aspects of food security and planetary health from different stages of food systems (more details in Supplementary Tables 4.1, 4.2, and 4.3). Out of the 30 structure and outcome metrics, 10 were excluded from our study due to insufficient observations for a comprehensive trend analysis (i.e., data available for less than 100 countries and/or 10 years of duration). We then assessed the remaining 20 metrics for the most appropriate scheme able to adequately compare the maximum number of countries with compatible observations and chronologies with our filter of best fit analysis (see Chapter 4, 4.3 Methods – 4.3.3 Data preparation), which directed the removal of 4 additional metrics and indicated the period between 1995 and 2015 as the most appropriate to avoid anachronic comparisons (Supplementary Table 4.5). Our final study sample was composed by: 8 structure metrics – agricultural area, synthetic fertiliser use, agricultural employment, gross agricultural output, Agricultural Total Factor Productivity, food imports, food exports, and Producer Price Index; 8 outcome metrics – forest area, Red List index, undernourishment, adult obesity, ecological footprint of consumption, agricultural greenhouse gas emissions (GHGE), land-use change and forestry GHGE, and agriculture, forestry and other land use (AFOLU) GHGE; and 3 socioeconomic indicators – income category, GDP per capita, and Human Development Index.

Global historical trends of both structure and outcome metrics of food systems substantially varied across the countries evaluated, measured by Compound Annual Change Rate (CACR – expressed as percentage of annual change). The combination of all possible clustering schemes evaluated by the cluster algorithm used (see Chapter 4 – 4.3 Methods), however, helped to identify patterns of co-transformation in five key structure metrics commonly shared across 161 countries: agricultural area, synthetic fertilizer use, agricultural employment, gross agricultural output, and Agricultural Total Factor Productivity. In practical terms, the cluster algorithm allocated countries to transformation archetypes by proximity of inter-country simultaneous rates of change in the five key structure metrics which then enabled comparison across archetypes.

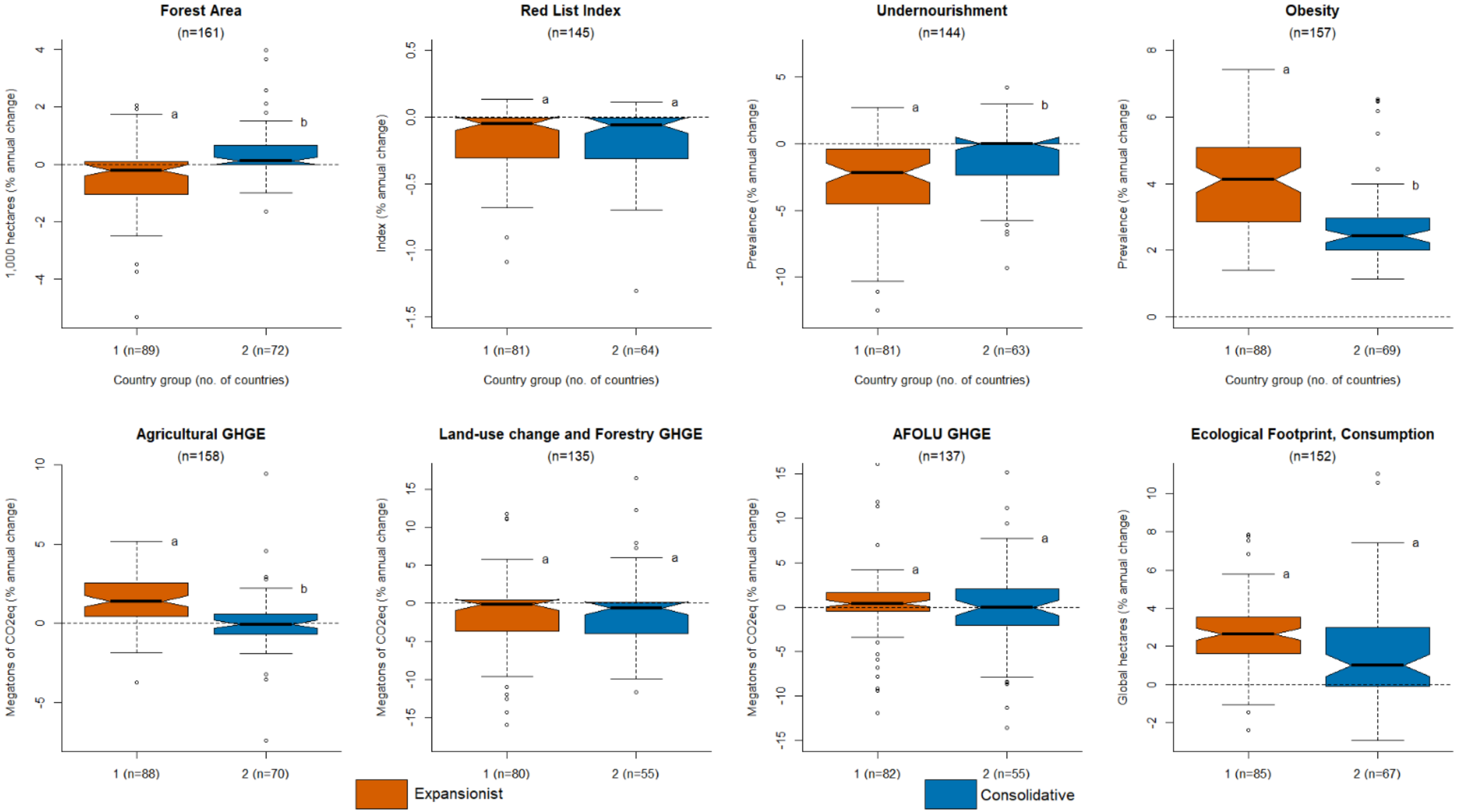
We found that from 60.9% to 91.3% of the combinations of all 30 cluster indexes indicated between two and four transformation archetypes as the most appropriate clustering scheme for all the countries explored (Supplementary Figure 4.3). Whilst the allocation of two different clusters categorised the countries by expansionist and consolidative transformation archetypes (n=89 and n=72 countries, respectively – Supplementary Figures 4.4 and 4.5), the assignment of three clusters further arranged the patterns of co-transformation in the expansionist group in a more refined manner, indicating rapidly expansionist, expansionist, and consolidative transformation archetypes (RETA=26, ETA=63, and CTA=72 countries, respectively; Figures 4.2 and S3). We found broadly similar results with alternative clustering schemes of either three or two transformation archetypes. In both cases, the expansionist and consolidative archetypes were clustered independently of their Agricultural Total Factor Productivity. Importantly, the sole difference between the expression of either three or four transformation archetypes by the cluster algorithm was represented by the country Singapore, which could be classified as a rapidly consolidative transformation archetypes on its own (Supplementary Figures 4.6 and 4.7). Thus, we express the main results of our study under three distinct transformation archetypes in global food systems from 1995 to 2015 (Supplementary Tables 4.6 and 4.7).



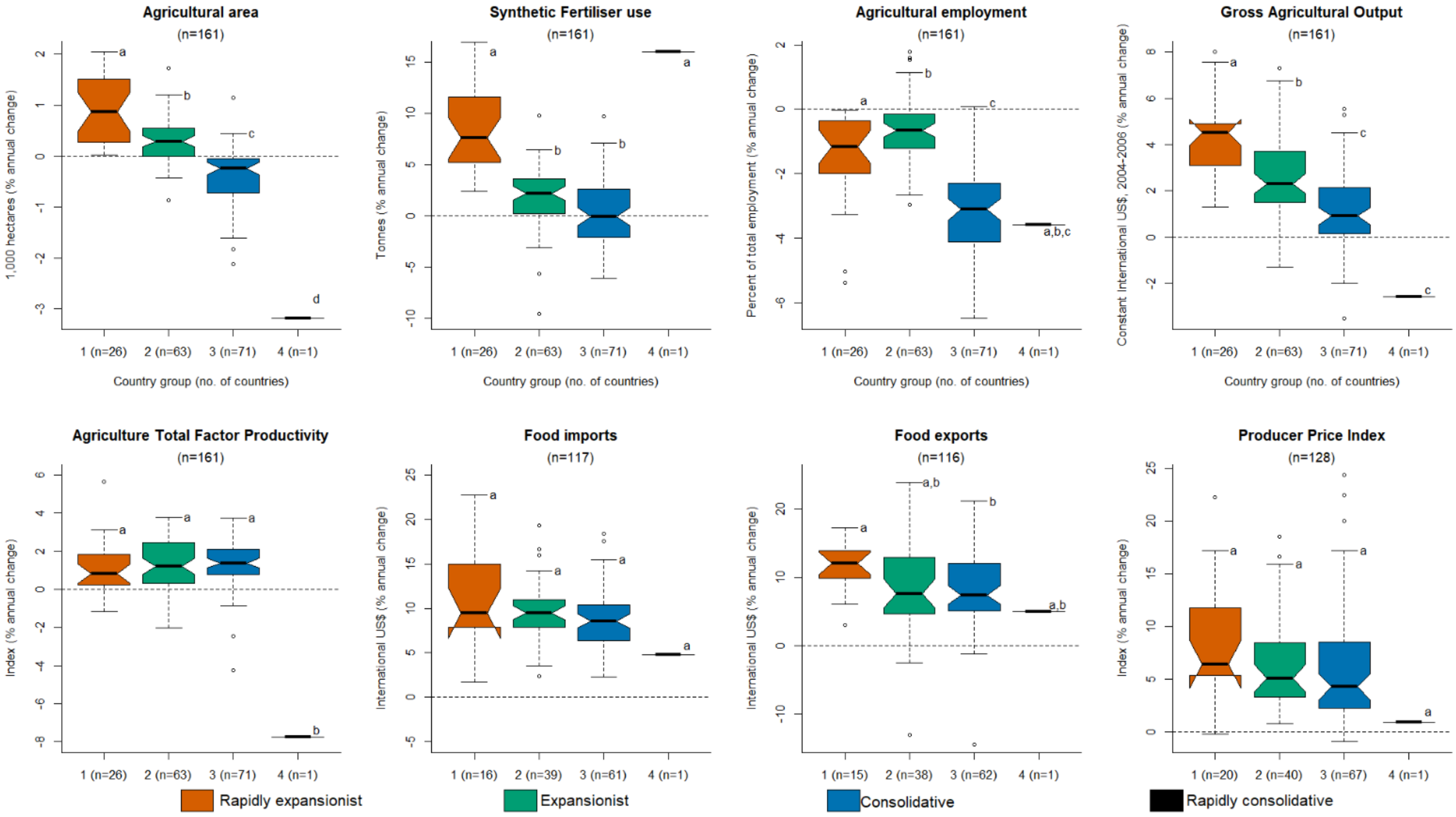
<u>Supplementary Figure 4.3</u> – Cluster dendrogram and most appropriate clustering schemes for the key structure metrics.


Agricultural area
(n=161)
1,000 hectares (% annual change)
2
1
0
-1
-2
-3
a
b
1 (n=89)
2 (n=72)
Country group (no. of countries)
Synthetic Fertiliser use
(n=161)
Tonnes (% annual change)
15
10
5
0
-5
-10
a
b
1 (n=89)
2 (n=72)
Country group (no. of countries)
Agricultural employment
(n=161)
Percent of total employment (% annual change)
2
0
-2
-4
-6
a
b
1 (n=89)
2 (n=72)
Country group (no. of countries)
Gross Agricultural Output
(n=161)
Constant International US$, 2004-2006 (% annual change)
8
6
4
2
0
-2
a
b
1 (n=89)
2 (n=72)
Country group (no. of countries)
Agriculture Total Factor Productivity
(n=161)
Index (% annual change)
6
4
2
0
-2
-4
-6
-8
a
a
1 (n=89)
2 (n=72)
Food imports
(n=117)
International US$ (% annual change)
25
20
15
10
5
0
-5
a
a
1 (n=55)
2 (n=62)
Food exports
(n=116)
International US$ (% annual change)
20
10
0
-10
a
a
1 (n=53)
2 (n=63)
Producer Price Index
(n=128)
Index (% annual change)
25
20
15
10
5
0
a
a
1 (n=60)
2 (n=68)
Expansionist
Consolidative

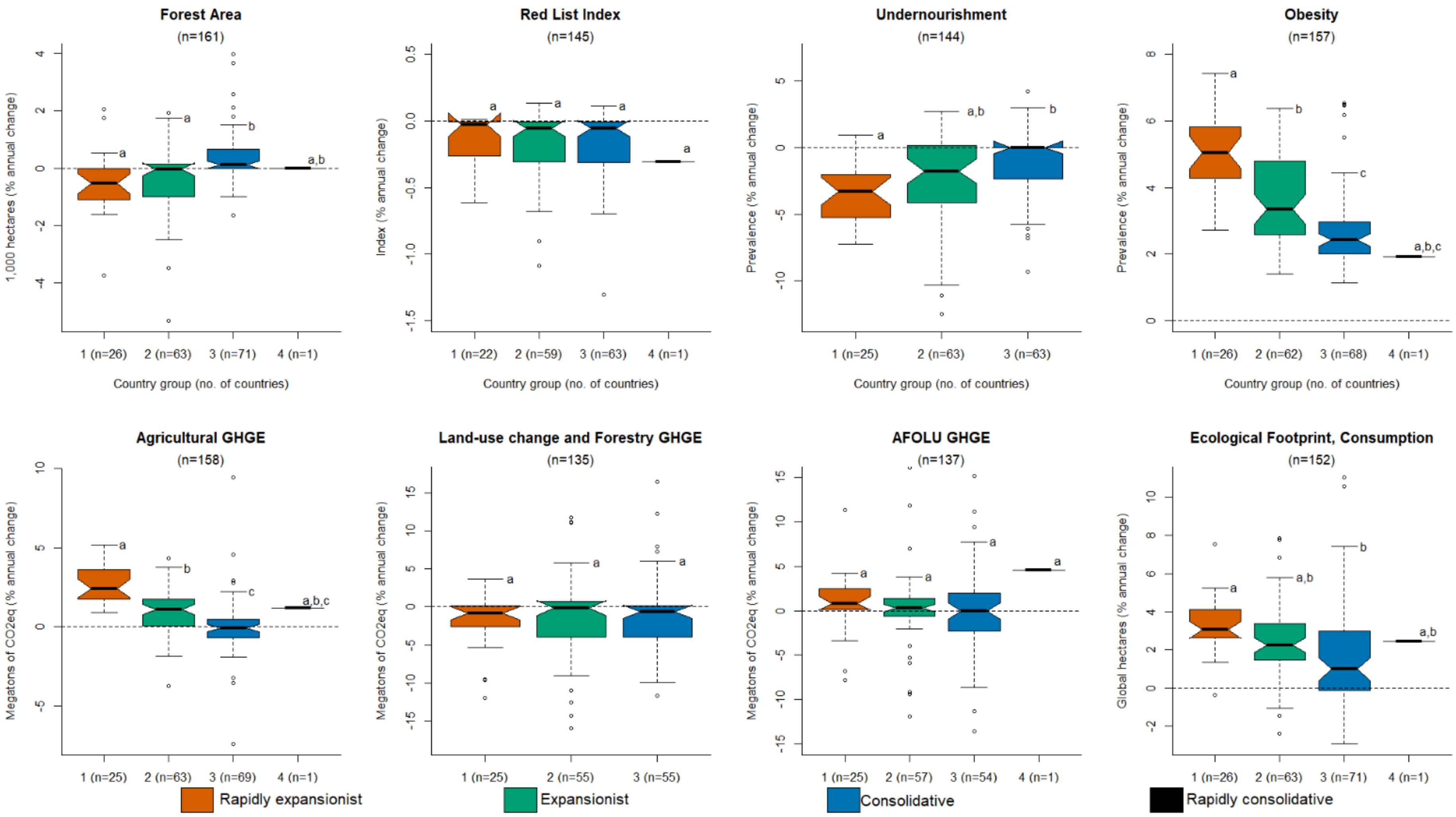
Supplementary Figure 4.4 (continued from previous page) – Global trends in structure metrics across two transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data observations beyond the extremes of the whiskers. Different lowercase letters a, b, and c on top of whiskers indicate significant differences at $p < 0.05$.


Forest Area
(n=161)
1,000 hectares (% annual change)
4
2
0
-2
-4
a
b
1 (n=89)
2 (n=72)
Country group (no. of countries)
Red List Index
(n=145)
Index (% annual change)
0.5
0.0
-0.5
-1.0
-1.5
a
a
1 (n=81)
2 (n=64)
Country group (no. of countries)
Undernourishment
(n=144)
Prevalence (% annual change)
5
0
-5
-10
a
b
1 (n=81)
2 (n=63)
Country group (no. of countries)
Obesity
(n=157)
Prevalence (% annual change)
8
6
4
2
0
a
b
1 (n=88)
2 (n=69)
Country group (no. of countries)
Agricultural GHGE
(n=158)
Megatons of CO2eq (% annual change)
10
5
0
-5
a
b
1 (n=88)
2 (n=70)
Land-use change and Forestry GHGE
(n=135)
Megatons of CO2eq (% annual change)
15
10
5
0
-5
-10
-15
a
a
1 (n=80)
2 (n=55)
AFOLU GHGE
(n=137)
Megatons of CO2eq (% annual change)
15
10
5
0
-5
-10
-15
a
a
1 (n=82)
2 (n=55)
Ecological Footprint, Consumption
(n=152)
Global hectares (% annual change)
10
8
6
4
2
0
-2
a
a
1 (n=85)
2 (n=67)
Expansionist
Consolidative

Supplementary Figure 4.5 (continued from previous page) – Global trends in outcome metrics across two transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data points beyond the extremes of the whiskers. Different lowercase letters a, b, and c on top of whiskers indicate significant differences at $p < 0.05$. Abbreviations: GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.


Agricultural area
(n=161)
1,000 hectares (% annual change)
2
1
0
-1
-2
-3
a
b
c
d
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Country group (no. of countries)
Synthetic Fertiliser use
(n=161)
Tonnes (% annual change)
15
10
5
0
-5
-10
a
b
b
a
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Country group (no. of countries)
Agricultural employment
(n=161)
Percent of total employment (% annual change)
2
0
-2
-4
-6
a
b
c
a,b,c
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Country group (no. of countries)
Gross Agricultural Output
(n=161)
Constant International US$, 2004-2006 (% annual change)
8
6
4
2
0
-2
a
b
c
c
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Country group (no. of countries)
Agriculture Total Factor Productivity
(n=161)
Index (% annual change)
6
4
2
0
-2
-4
-6
-8
a
a
a
b
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Food imports
(n=117)
International US$ (% annual change)
25
20
15
10
5
0
-5
a
a
a
a
1 (n=16)
2 (n=39)
3 (n=61)
4 (n=1)
Food exports
(n=116)
International US$ (% annual change)
20
10
0
-10
a
a,b
b
a,b
1 (n=15)
2 (n=38)
3 (n=62)
4 (n=1)
Producer Price Index
(n=128)
Index (% annual change)
25
20
15
10
5
0
a
a
a
a
1 (n=20)
2 (n=40)
3 (n=67)
4 (n=1)
🟧 Rapidly expansionist
🟩 Expansionist
🟦 Consolidative
⬛ Rapidly consolidative

<u>Supplementary Figure 4.6 (continued from previous page)</u> – Global trends in structure metrics across four transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data observations beyond the extremes of the whiskers. Different lowercase letters a, b, and c on top of whiskers indicate significant differences at $p < 0.05$.


Forest Area
(n=161)
1,000 hectares (% annual change)
4
2
0
-2
-4
a
a
b
a,b
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
Country group (no. of countries)
Red List Index
(n=145)
Index (% annual change)
0.5
0.0
-0.5
-1.0
-1.5
a
a
a
a
1 (n=22)
2 (n=59)
3 (n=63)
4 (n=1)
Country group (no. of countries)
Undernourishment
(n=144)
Prevalence (% annual change)
5
0
-5
-10
a
a,b
b
1 (n=25)
2 (n=63)
3 (n=63)
Country group (no. of countries)
Obesity
(n=157)
Prevalence (% annual change)
8
6
4
2
0
a
b
c
a,b,c
1 (n=26)
2 (n=62)
3 (n=68)
4 (n=1)
Country group (no. of countries)
Agricultural GHGE
(n=158)
Megatons of CO2eq (% annual change)
10
5
0
-5
a
b
c
a,b,c
1 (n=25)
2 (n=63)
3 (n=69)
4 (n=1)
Land-use change and Forestry GHGE
(n=135)
Megatons of CO2eq (% annual change)
15
10
5
0
-5
-10
-15
a
a
a
1 (n=25)
2 (n=55)
3 (n=55)
AFOLU GHGE
(n=137)
Megatons of CO2eq (% annual change)
15
10
5
0
-5
-10
-15
a
a
a
a
1 (n=25)
2 (n=57)
3 (n=54)
4 (n=1)
Ecological Footprint, Consumption
(n=152)
Global hectares (% annual change)
10
8
6
4
2
0
-2
a
a,b
b
a,b
1 (n=26)
2 (n=63)
3 (n=71)
4 (n=1)
🟧 Rapidly expansionist
🟩 Expansionist
🟦 Consolidative
⬛ Rapidly consolidative

Supplementary Figure 4.7 (continued from previous page) – Global trends in outcome metrics across four transformation archetypes in global food systems of 161 countries from 1995 to 2015. Values are expressed by medians, coloured boxplot hinges indicate the range between the 1st and 3rd quartiles, whiskers indicate 1.5 times the distance from the nearest hinge, and individual points are data points beyond the extremes of the whiskers. Different lowercase letters a, b, and c on top of whiskers indicate significant differences at $p < 0.05$. Abbreviations: GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.

Supplementary Table 4.6 – Rates of annual change of all structure, outcome, and socioeconomic metrics across transformation archetypes in global food systems in 161 countries from 1995 to 2015.

	Mean			**Median**		
Metric	**RETA**	**ETA**	**CTA**	**RETA**	**ETA**	**CTA**
Structure metrics						
Agriculture area	0.93%	0.29%	-0.44%	0.86%	0.28%	-0.24%
Synthetic fertilizer use	8.73%	1.74%	0.51%	7.57%	2.19%	0.02%
Agricultural employment	-1.4%	-0.64%	-3.22%	-1.15%	-0.65%	-3.11%
Gross Agricultural Output	4.41%	2.62%	1.08%	4.52%	2.31%	0.89%
Agricultural Total Factor Productivity	1.03%	1.29%	1.21%	0.81%	1.2%	1.36%
Food import	11.14%	9.58%	8.92%	9.46%	9.48%	8.43%
Food export	13.46%	8.61%	8.28%	12.04%	7.64%	7.4%
Producer Price Index, Agriculture	8.38%	6.47%	6.14%	6.41%	5.09%	4.26%
Outcome metrics						
Forest area	-0.5%	-0.37%	0.37%	-0.53%	-0.03%	0.12%
Red List Index	-0.13%	-0.17%	-0.18%	-0.03%	-0.3%	-0.31%
Ecological Footprint of Consumption	3.35%	2.47%	1.7%	3.05%	2.24%	0.99%
Undernourishment	-3.26%	-2.17%	-1.27%	-3.27%	-1.77%	0.0%
Obesity	5.00%	3.61%	2.69%	5.04%	3.34%	2.42%
Agricultural total GHGE	2.62%	1.05%	0.08%	2.42%	1.05%	-0.05%
Land-use change and Forestry total GHGE	-1.77%	-2.3%	-1.07%	-0.82%	-0.16%	-0.66%
AFOLU total GHGE	0.86%	0.02%	0.53%	0.84%	0.33%	-0.05%
Socioeconomic metrics						
GDP per capita, nominal	1.71%	0.04%	0.79%	3.5%	1.86%	2.8%
GDP per capita, PPP	-0.36%	2.45%	0.59%	2.45%	2.14%	2.13%
Human Development Index (HDI)	1.68%	0.99%	0.68%	1.57%	0.97%	0.67%

Abbreviations: RETA – Rapidly Expansionist Transformation Archetype; ETA – Expansionist Transformation Archetype; CTA – Consolidative Transformation Archetype; GHGE – Greenhouse gases emissions; AFOLU – Agriculture, Land-Use Change and Forestry; PPP – Purchasing Power Parity.

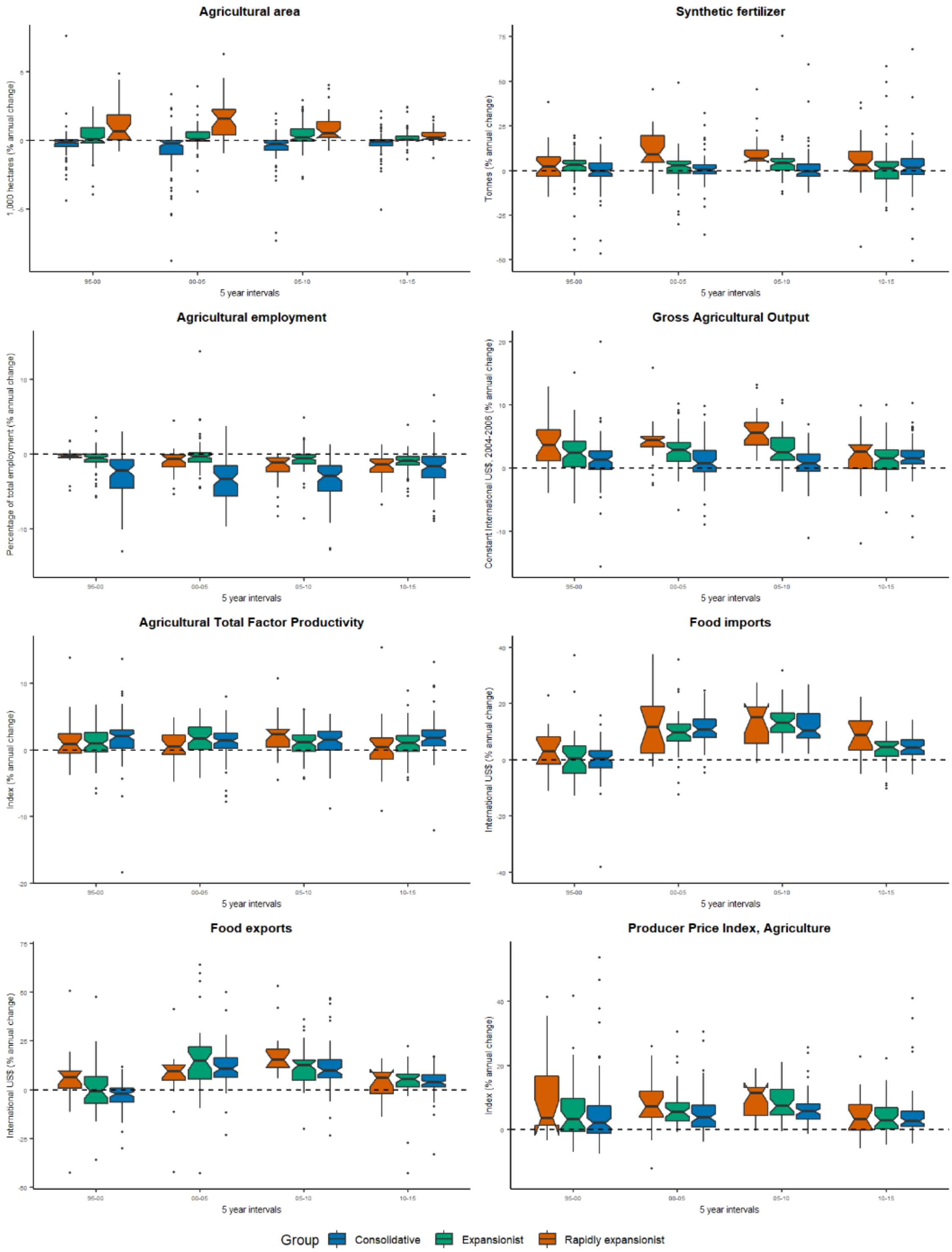
Supplementary Table 4.7 – Significance testing of all structure, outcome, and socioeconomic metrics across transformation archetypes in global food systems in 161 countries from 1995 to 2015.

Metric	**F value**	**Degrees of freedom**	**Pr (>F)**	**RETA - ETA (p adj.)**	**RETA - CTA (p adj.)**	**ETA - CTA (p adj.)**
Structure metrics						
Agriculture area	62.35	2 – 158	< 2 x 10^{-16}***	< **0.001**	< **0.001**	< **0.001**
Synthetic fertilizer use	52.42	2 – 158	< 2 x 10^{-16}***	< **0.001**	< **0.001**	0.116
Agricultural employment	76.43	2 – 158	< 2 x 10^{-16}***	**0.024**	< **0.001**	< **0.001**
Gross Agricultural Output	36.61	2 – 158	8.63 x 10^{-14}***	< **0.001**	< **0.001**	< **0.001**
Agricultural Total Factor Productivity	0.245	2 – 158	0.783	0.764	0.87	0.957
Food import	2.108	2 – 114	0.126	0.369	0.108	0.686
Food export	3.769	2 – 113	0.026 *	**0.049**	**0.021**	0.97
Producer Price Index (PPI), Agriculture	1.441	2 – 125	0.241	0.376	0.214	0.947
Outcome metrics						
Forest area	11.13	2 – 158	3 x 10^{-05}***	0.855	**0.001**	< **0.001**
Red List Index	0.383	2 – 142	0.683	0.729	0.67	0.991
Ecological Footprint of Consumption	5.732	2 – 149	0.004 **	0.198	**0.003**	0.116
Undernourishment	3.94	2 – 141	0.022 *	0.304	**0.019**	0.255
Obesity	32.73	2 – 154	1.43 x 10^{-12}***	< **0.001**	< **0.001**	< **0.001**
Agricultural total GHGE	21.77	2 – 155	4.66 x 10^{-09}***	< **0.001**	< **0.001**	**0.003**
Land-use change and Forestry total GHGE	0.369	2 – 132	0.692	0.953	0.921	0.667
AFOLU total GHGE	0.22	2 – 134	0.803	0.813	0.969	0.884
Socioeconomic metrics						
GDP per capita, nominal	0.38	2 – 155	0.684	0.672	0.883	0.865
GDP per capita, PPP	1.439	2 – 155	0.24	0.295	0.863	0.383
Human Development Index (HDI)	32.97	2 – 132	2.43 x 10^{-12}***	< **0.001**	< **0.001**	**0.003**

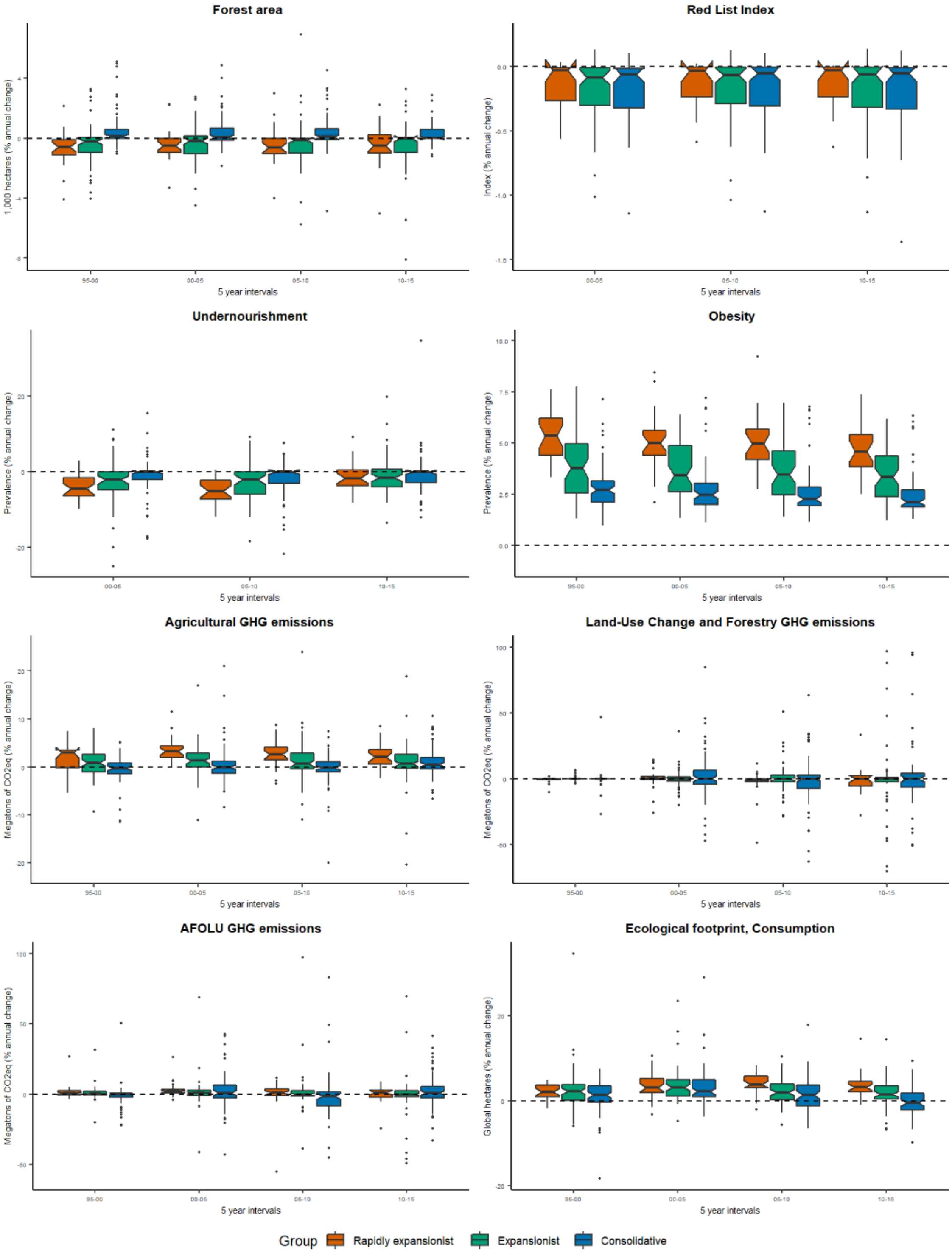
Adjusted P-values across transformation archetypes (RETA = Rapidly expansionist, ETA = Expansionist, and CTA = Consolidative) are described by * < 0.05, ** < 0.01, and *** < 0.001. Bold values express significant difference between archetypes. Abbreviations: Abbreviations: GHGE: Greenhouse gases emissions; AFOLU – Agriculture, Land-Use Change and Forestry; PPP – Purchasing Power Parity.

A4.6 Five-year intervals analysis

Our analysis of five-year intervals revealed similar comparative rates of change across the three transformation archetypes. In other words, in each of the four five-year intervals (i.e., 1995 – 2000, 2000 – 2005, 2005 – 2010, and 2010 – 2015), RETA tended to exhibit steeper rates of change than those expressed by ETA, whilst CTA followed a similar pattern of relative stability identified in the same seven metrics of the wider period between 1995 and 2015. These metrics were agricultural area, synthetic fertiliser use, gross agricultural output, undernourishment, obesity, agricultural GHGE, and ecological footprint of consumption. In general, within-archetypes variability did not differ in patterns of change for each of the five-year intervals in comparison to the entire period of analysis (Supplementary Figures 4.8 and 4.9). Exceptions to this behaviour were identified for agricultural employment, food imports and exports, and for ecological footprint of consumption. The rate of change in agricultural employment displayed by RETA seemed to be in accelerating reduction across the 5-years intervals. Food imports and food exports showed more intense rates of change within the same transformation archetypes in 00-05 and in 05-10 than in 95-00 and 10-15. Finally, rates of change in ecological footprint of consumption started expressing different rates of change across transformation archetypes only in 05-10 and 10-15. These differences were mainly due decreasing trajectories shown by CTA, moving towards stability.



Supplementary Figure 4.8 – Global trends in 5-year intervals of structure metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015.



Supplementary Figure 4.9 – Global trends in 5-year intervals of outcome metrics across transformation archetypes in global food systems of 161 countries from 1995 to 2015. Abbreviations: GHGE – greenhouse gases emissions; AFOLU – Agriculture, Forestry and Other Land Use.

Methodological reflections to chapter 4

Enabling foundations for food systems efficiency

Despite global consensus that food systems ought to be sustainable and capable of delivering affordable and safe food to nourish people (Pradhan et al., 2017), many of their associated health, environmental, and economic outcomes are not aligned in this direction. The framing of environmental overexploitation, for instance, either as an accepted or as a problematic ‘externality’ derived from food systems practices in order to feed people (Sukhdev et al., 2016) is a partial evaluation of trends across the globe over the past decades to begin with. Global food systems, in general, have been simultaneously transgressing planetary boundaries and delivering inadequate quantity and quality of food in a highly concerning, inefficient manner. Moreover, these coexistent trends have not been associated with improved levels of socioeconomic wellbeing nor dependent on agricultural extent in countries which followed more expansionist pathways. A primary step needed to enable adequate discussions and the development of appropriate interventions in the presence of such complex social-ecological challenges is a reform of paradigms, metrics, and assessment models.

Different cultural and disciplinary values underpin the paradigms embedded in scientific enquires of global food systems (Dornelles et al., 2020). When conventional paradigms cannot satisfactorily accommodate the complex intertwined food challenges (e.g. a predominant view of productivity or other reductionist approaches), it is needed to reconsider more appropriate tools able of analysing dynamic food linkages and their emergent properties and thus embrace systems-thinking (Ingram et al., 2020). As such, a paradigm of systemic efficiency can potentially guide the development of more reliable, effective, and timely interventions in global food systems (“From Silos to Systems,” 2020). In parallel with an emergent paradigm of systems efficiency comes the logical need for more comprehensive metrics (Sukhdev, 2018). Metrics that are specific enough to enable reliable qualitative or quantitative measurements, but that also integrate the hidden costs and benefits of 'externalities' throughout the food value chain (Sukhdev et al., 2016) and expand the assessment of productivity beyond capital inputs and outputs to more robust outcomes such as number of people nourished (Benton & Bailey, 2019). Similar distinctions for the selection of valid endpoints in decision-making processes are commonly discussed, for instance, in the field of epidemiology, in which surrogate outcomes (e.g., high-systolic blood pressure in patients with hypertension) are interpreted differently from clinical or final outcomes (e.g., stroke or myocardial infarction - Ciani et al., 2017). Thus, as an outcome, the amount of food output per unit input should not be attributed the same relevance to the number of people that can be fed healthily and sustainably per unit input.

Assessment models of global food systems need to be reconsidered and aligned with the emergence of more appropriate paradigms and metrics. Similarly to our application of cluster algorithms derived from systems ecology with more conventional macro-economic measurements, models can be more integrative (i.e. recognise the interdependence, coexistence, and non-linearity of variables), adaptable (i.e. diverge from restrictive disciplinary premises when they do not appropriately recognise real world priorities), and can promote humility and reflexivity (i.e. recognise different cultural values and perspectives that underpin scientific disciplines to avoid incommensurable propositions). Research in systems of harvestable biomass has been incorporating these principles to explore potential trade-offs and synergies, for instance, between food security and protection of biodiversity or between short- and long-term novel and pervasive risks in global production ecosystems (Nyström et al., 2019). Finally, guiding principles of transparency (Nyström et al., 2019) and transdisciplinary collaboration (Lang et al., 2012) are fundamentally needed not only to prevent the immeasurability of setbacks but also to improve the plausibility to make the most of windows of opportunity and policy levers (e.g., the Nuffield Ladder of Policy Intervention to Healthy Diets from Sustainable Food Systems - Willett et al., 2019) with multi-stakeholder leadership (P. Olsson et al., 2006).

Appendix 4

Scripts to chapter 4

In our study, all steps in data preparation and analysis were conducted in the software R version 3.6.1, and the scripts containing the code used are synthesized in Supplementary Table 4.8. The scripts were organized by its different parts, and instructions were provided in each file to facilitate its replication.

Supplementary Table 4.8 – R scripts used in this study.

File name	Description	Parts
1_Dornelles.et.al_ Data.standardisation	This code standardise all metrics acquired by 'country', 'year', and 'value' to generate collated files, following hierarchical order of metrics: individual variables, derived variables, and aggregated indicators.	1. Structure metrics 2. Outcome metrics 3. Other metrics
2_Dornelles.et.al_ Duration.and.filter	This is script is responsible for analysing the duration of all metrics acquired, and for identifying the filter of best fit to be applied for the computation of the trend analysis.	1. Upload collated files 2. Calculation of time intervals 3. Duration analysis 4. Filter of best fit analysis
3_Dornelles.et.al_ Trends.structure	This script calculates the adjusted Compound Annual Changed Rate (CACR) for all structure metrics.	1. Upload collated files 2. Calculate the trend analysis. 3. Generate the trend results for structure metrics
4_Dornelles.et.al_ Trends.outcomes	This script calculates the adjusted Compound Annual Changed Rate (CACR) for all outcome metrics.	1. Upload collated files 2. Calculate the trend analysis. 3. Generate the trend results for outcome metrics
5_Dornelles.et.al_ Cluster.algorithm	This script aggregates countries into transformation archetypes (clusters) based on the trends of key structure metrics and apply significance testing to identify differences between country groups. Plots of transformation archetypes: 1) Structure metrics, 2) Outcome metrics, 3) World map, and 4) Carrying capacity.	1. Upload trend results 2. Cluster algorithm 3. Significance testing 1 4. Transformation archetypes 1 5. Transformation archetypes 2 6. Significance testing 2 7. World map 8. Carrying capacity
6_Dornelles.et.al_ Five.year.intervals	This script calculates the longitudinal trends in the transformation archetypes (clusters), disaggregated in intervals of 5 years since 1995 (1995-2000; 2000-2005; 2005-2010; 2010-2015).	1. Upload collated files 2. Calculate trend analysis per 5 year-intervals 3. Generate the trend results for each metric 4. Five-year intervals
7_Dornelles.et.al_ Country.profiles	This scrip aggregates the longitudinal observations of the sixteen structure and outcome metrics assessed to navigate the transformation archetypes in global food systems for all 161 countries from 1995 to 2015 and generate individual pdf files for each country profile.	1. Upload trend results and longitudinal observations 2. Generate country profiles

The extension off all scripts used in this study are '.R'.

APPENDIX 5

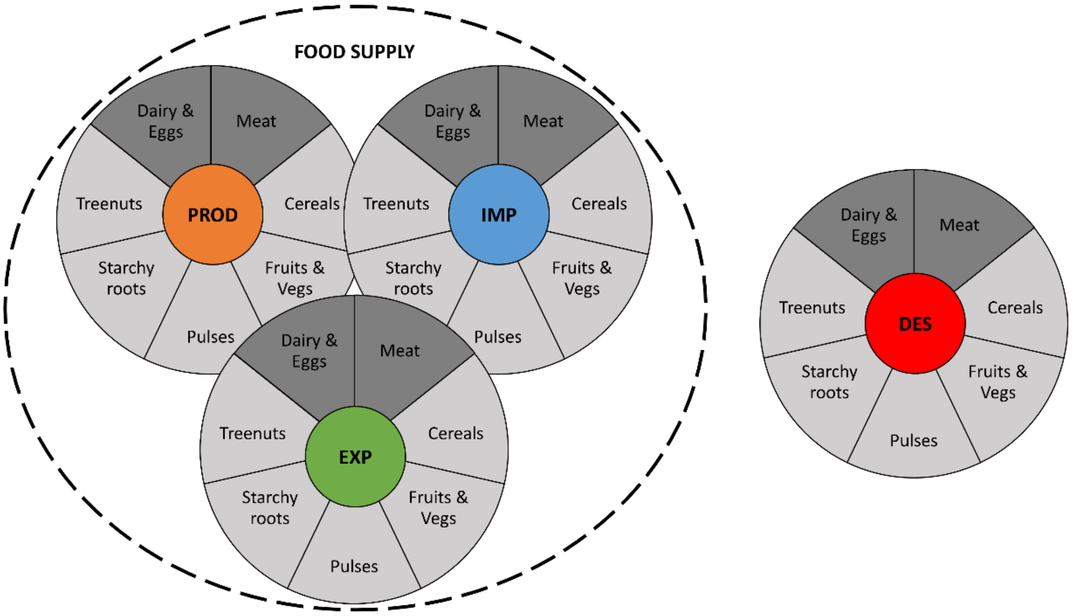
SUPPLEMENTARY MATERIAL TO CHAPTER 5

Systemic food risks: synchronised dynamics of shocks to national food availability and supply.

This appendix includes:

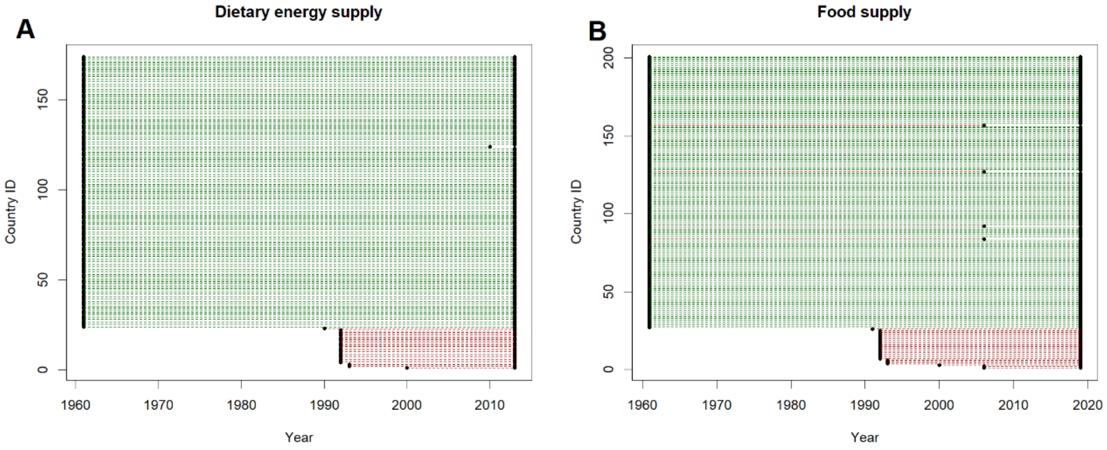
- Supplementary Figure 5.1 – Illustrative representation of food supply and dietary energy supply with their respective components and food groups.
- Supplementary Figure 5.2 – Period of coverage across countries for dietary energy supply (A) and food supply (B).
- Supplementary Table 5.1 – Filter to determine countries with sufficient timeseries data for inclusion in our analysis for dietary energy supply and food supply.
- Supplementary Figure 5.3 – Total dietary energy supply (A), interannual fluctuations of dietary energy supply (B), prevalence of obesity (C), and prevalence of undernourishment (D) across clusters of interannual fluctuations in dietary energy supply from 1961 to 2013.
- Supplementary Figure 5.4 – Total food supply (A), interannual fluctuations of food supply (B), prevalence of obesity (C), and prevalence of undernourishment (D) across clusters of interannual fluctuations in food supply from 1961 to 2013.

Supplementary Figure 5.1 – Illustrative representation of food supply and dietary energy supply with their respective components and food groups.



Food production, imports, and exports represent the components of food supply. The nine food groups of dietary energy supply and food supply are divided into crops (i.e., cereals, fruits, treenuts, pulses, starchy roots, and vegetables – as light grey) and livestock (i.e., meat, milk, and eggs – as dark grey). Abbreviations: PROD: food production; IMP: food imports; EXP: food exports; DES: Dietary energy supply.

Supplementary Figure 5.2 – Period of coverage across countries for dietary energy supply (A) and food supply (B).



Each horizontal segment represents the period of coverage (in years, in the x axis) for a particular country (as country ID, in the y axis). Colouring scheme: dark green indicates countries with sufficient timeseries data for inclusion in our analysis (at 90% of the total duration from 1961 to 2013) and dark red represent countries which were excluded by the filter.

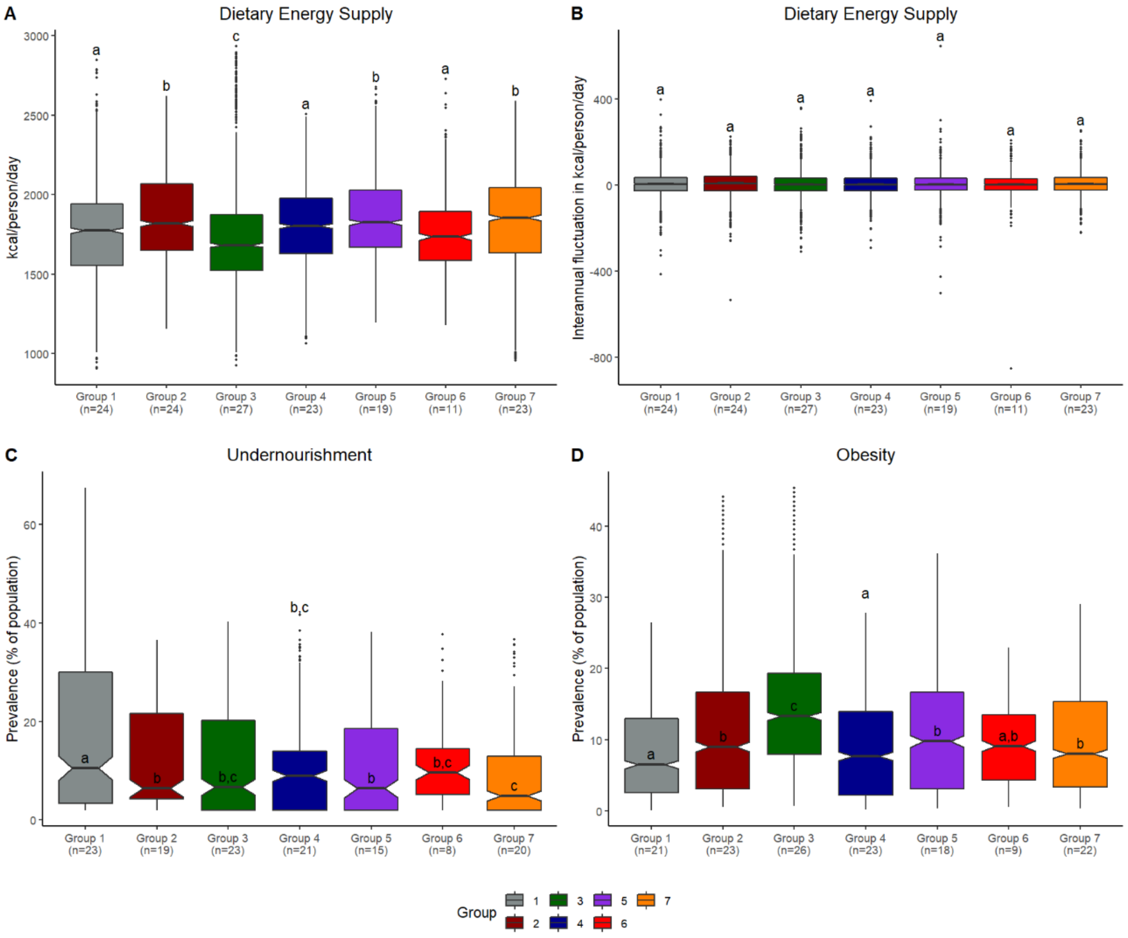
Appendix 5

Supplementary Table 5.1 – Filter to determine countries with sufficient timeseries data for inclusion in our analysis for dietary energy supply and food supply.

Initial year	Last year	Filter at 90%	Filter at 80%	Filter at 70%
Dietary energy supply				
1961	2013	151	151	151
1980	2013	151	151	152
1990	2013	170	173	173
1995	2013	172	173	174
2000	2013	173	173	174
2005	2013	173	173	173
1961	2005	151	151	151
1980	2005	151	151	151
1990	2005	152	173	173
1995	2005	173	173	173
2000	2005	174	174	174
Food supply				
1961	2013	171	175	175
1980	2013	171	191	198
1990	2013	194	195	199
1995	2013	195	195	197
2000	2013	197	197	197
2005	2013	197	197	197
1961	2005	175	175	175
1980	2005	175	175	175
1990	2005	176	198	198
1995	2005	198	198	198
2000	2005	199	199	199

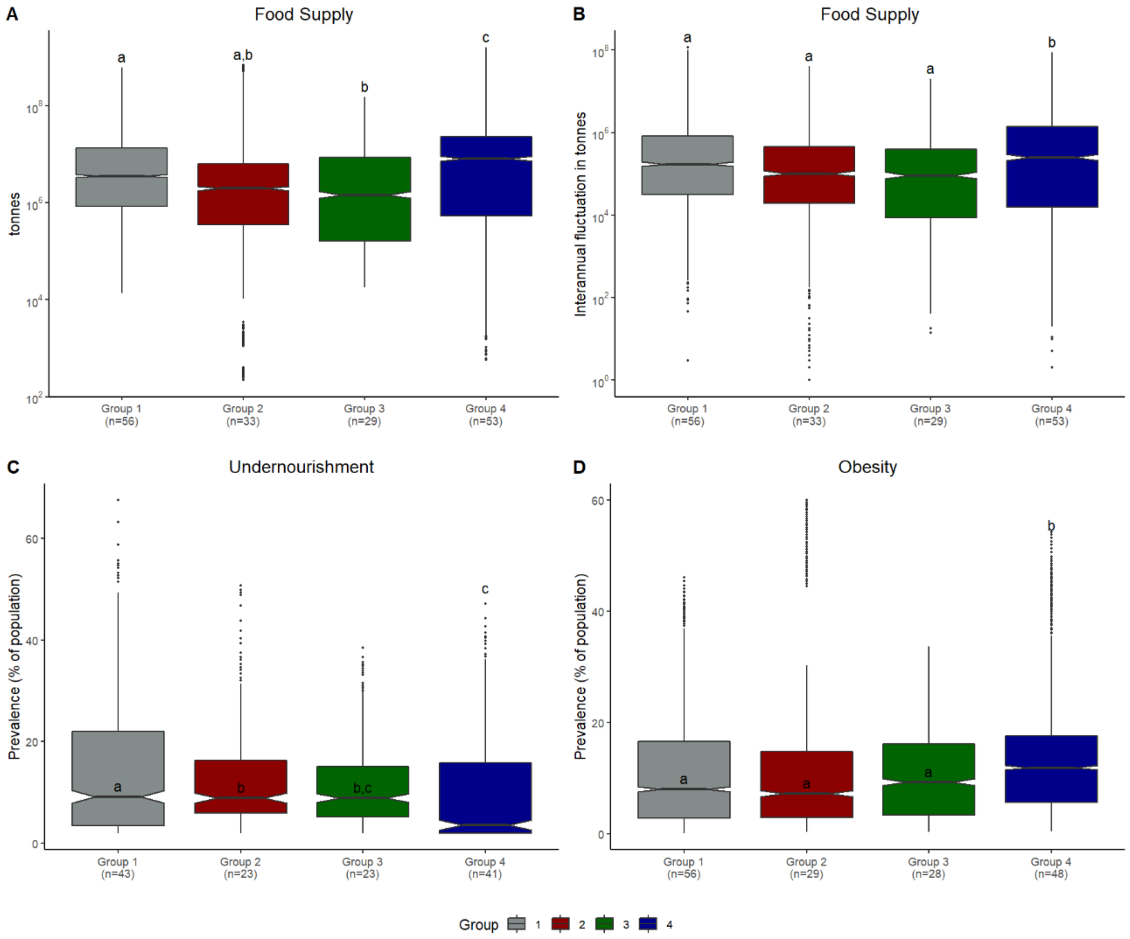
Shown are the number of countries within specific periods (e.g., 1961-2013 for the first row) that exceed distinct thresholds of time coverage for each period (i.e., 70%, 80%, and 90%).

Supplementary Figure 5.3 – Total dietary energy supply (A), interannual fluctuations of dietary energy supply (B), prevalence of undernourishment (C), and prevalence of obesity (D) across clusters of interannual fluctuations in dietary energy supply from 1961 to 2013.



Results are expressed in kcal/person/day, in delta of kcal/person/day between years, and as prevalence (% of total population).

Supplementary Figure 5.4 – Total food supply (A), interannual fluctuations of food supply (B), prevalence of undernourishment (C), and prevalence of obesity (D) across clusters of interannual fluctuations in food supply from 1961 to 2013.



Results are expressed in tonnes, in delta of tonnes between years, and as prevalence (% of total population)