CHAPTER 2

SYSTEMS THINKING: AN APPROACH FOR UNDERSTANDING 'ECO-AGRI-FOOD SYSTEMS'

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SUMMARY

Chapter 2 makes the case for using systems thinking as a guiding perspective for TEEBAgriFood's development of a comprehensive Evaluation Framework for the eco-agri-food system. Many dimensions of the eco-agri-food system create complex analytical and policy challenges. Systems thinking allows better understanding and forecasting of the outcomes of policy decisions by illuminating how the components of a system are interconnected with one another and how the drivers of change are determined and impacted by feedback loops, delays and non-linear relationships. To establish the building blocks of a theory of change, systems thinking empowers us to move beyond technical analysis and decision-tool toward more integrated approaches that can aid in the forming of a common ground for cultural changes.

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2.0 KEY MESSAGES

- This chapter makes the case for using systems thinking as a guiding perspective for TEEBAgriFood’s development of a comprehensive Evaluation Framework for the eco-agri-food system.
- ‘Eco-agri-food systems’ is our collective term for the vast and interacting complex of ecosystems, agricultural lands, pastures, inland fisheries, labour, infrastructure, technology, policies, culture, traditions, and institutions (including markets) that are variously involved in growing, processing, distributing and consuming food.
- Diverse agricultural production systems grow our crops and livestock and employ more people than any other economic sector. They are underpinned by complex biological and climatic systems at local, regional and global levels. These natural systems are overlaid by social and economic systems, which transform agricultural production into food and finally deliver it to people based on market infrastructure, economic forces, government policies, corporate strategies and consumer and societal preferences. Furthermore, technologies, information and culture are continually re-shaping production, distribution and consumption, as well as the interactions among them.
- The global food system is one of the most important drivers of planetary transformation and it is experiencing multiple failures. Many dimensions of the eco-agri-food system create complex analytical and policy challenges. In the end, the state of human wellbeing, including the health of people and the planet, is determined by the diverse interlinked “eco-agri-food systems” and consumer choices made within these systems.
- Eco-agri-food systems are more than production systems. Using one-dimensional metrics such as “per hectare productivity” ignores the negative consequences and the trade-offs across multiple domains of human and planetary wellbeing and fails to account for the various dimensions of sustainability.
- Silo approaches are limiting our ability to achieve a comprehensive understanding of the interconnected nature of the eco-agri-food system challenges. We need a holistic framework that allows the integration of well-understood individual pieces into a new, complete picture.
- Systems thinking allows better understanding and forecasting of the outcomes of policy decisions by illuminating how the components of a system are interconnected with one another. Systems thinking identifies the drivers of change as determined and impacted by feedback loops, delays and non-linear relationships. Synergies and coherence can be gained when evidence is generated and used based on concepts and methods aligned with systems thinking.
- In the context of TEEBAgriFood, an important role of systems thinking is to identify the main components, drivers, dynamics and relationships that impact the entire value chain of the eco-agri-food system. This helps make side effects and tradeoffs visible, allows for identification of winners and losers, and uncovers synergies that can be realized through the implementation of public policies or other behaviour interventions.
- To establish the building blocks of a theory of change, systems thinking empowers us to move beyond technical analysis and decision-tool toward more integrated approaches that can aid in the forming of a common ground for cultural changes.

CHAPTER 2

SYSTEMS THINKING AN APPROACH FOR UNDERSTANDING 'ECO-AGRI-FOOD SYSTEMS'

2.1 INTRODUCTION

Our crops and livestock arise from diverse agricultural production systems that employ more people than any other economic sector globally (ILO 2014). These production systems are underpinned by complex biological and climatic systems at local, regional and global levels. Overlaying these production systems are social systems, including those involved with agricultural production and the transformation of crops into food, fuels and fibre. A third layer consists of economic systems, which deliver agricultural products to people, based on market forces, available infrastructure, government policies, and corporate strategies, all of which interact with consumer preferences and broader societal norms. Many of the interactions, both within and across systems, involve "externalities" (positive or negative), described in economics as the cost or benefit that affects a party who did not choose to incur that cost or benefit (Buchanan and Stubblebine 1962). Furthermore, technologies, information, divergent views, and culture are continually re-shaping production, distribution, and consumption modes, as well as the interactions among them. In the end, the state of many dimensions of human wellbeing, including the health of people and of the planet, are affected by the diverse interlinked food systems and the consumer choices made within these systems. In this report, the eco-agri-food system refers to the vast and interacting complex of ecosystems, agricultural lands, pastures, inland fisheries, labour, infrastructure, technology, policies, culture, traditions, and institutions (including markets) that are variously involved in growing, processing, distributing and consuming food.

The global food system, one of the most important drivers of planetary transformation (Rockström *et al.* 2009a; Rockström *et al.* 2009b; Ehrlich and Ehrlich 2013), is "failing", and the "business-as-usual" model is not working (Vivero-Pol 2017; IFPRI 2016; IAASTD 2009; Rosin *et al.* 2012a; Rosin *et al.* 2012b). The Global Food Policy Report (IFPRI 2016, p.6) points out the failures of the current food system:

On the one hand, it feeds more than 6 billion people—more than many in earlier decades and centuries would have believed possible. On the other hand, it leaves nearly 800 million people hungry. It does not provide all people with a healthy, safe, and nutritious diet; many of those who get sufficient calories are still malnourished. The food system does not generate adequate livelihoods for millions of people employed in the food system. And in a context of scarce and degraded natural resources and advancing climate change, it is not environmentally sustainable.

Humans are the main driver of change in the epoch in which we live, the new geological era some refer to as the Anthropocene (Rockström *et al.* 2009a; Steffen *et al.* 2011; Steffen *et al.* 2015). Much of this transformation has been driven by the commercialization of production and the mechanization of agriculture globally (see **Box 2.1** for an example), but failure by markets and governments to address externalities that affect social and environmental integrity have also contributed to the problem. The negative impact of human activity on the natural world has reached crisis levels. Terrestrial vertebrate populations declined by an astonishing 58 per cent between 1970 and 2010 (WWF 2016). Invertebrate populations show a global decline of about 45 per cent over the past 40 years (Dirzo *et al.* 2014). Similar declines have been documented for marine species (McCauley *et al.* 2015). Much of the declines in wildlife is attributed to habitat loss, pollution and over-exploitation associated with food production systems (Rockström *et al.* 2009a; Godfray *et al.* 2010; Amundson *et al.* 2015). Livestock production is the largest source of anthropogenic alteration to global phosphorus and nitrogen cycles. Since the 1950s, surpluses in these nutrients have increased by a factor of four and five, respectively (Bouwman *et al.* 2013). Excess quantities of these nutrients entering waterways are the leading causes of freshwater and marine eutrophication and the emergence of dead zones affecting aquatic life. Soil loss and terrestrial nutrient depletion are also accelerating (Baveye *et al.* 2016).

Furthermore, the expansion of industrial agriculture in many cases has had adverse social consequences for human communities (Ehrlich and Ehrlich 2013). Land-insecure smallholders, family farmers and peri-urban settlers are being pushed off land they have traditionally cultivated in many parts of the world, in the face of commercialization and the purchase of large tracts of land by foreign or absentee investors (De Schutter 2011; Rulli *et al.* 2013; Thorn *et al.* 2015). Many such cases have been documented in Latin America (Arancibia 2013; Carrizo and Berger 2012; Lapegna 2013; 2017; Leguizamón 2014a). In addition to a host of social impacts, such displacement leads to the loss of the local, experiential knowledge that is essential for site-appropriate agricultural production practices. Locally adapted cultivars and breeds may be lost, reducing agricultural biodiversity.

Seeking an ecologically sustainable and socially fair transition out of the current crisis has become an issue of utmost priority (Vivero-Pol 2017). Multiple voices have called for a paradigm shift in the structure and operation of the global food system (IAASTD 2009; Watson 2012; Rosin *et al.* 2012b), although the values, narratives, economic and moral foundations of that new aspirational and inspirational paradigm have not yet been fully developed (Vivero-Pol 2017). The application of systems thinking to understanding and managing the complexity of the global eco-agri-food system is an important step in achieving this transformation (Bosch *et al.* 2007; UNEP 2011). In this report, TEEBAgriFood sets out to evaluate the reality of today's highly complex "eco-agri-food" systems. By making the invisibles (externalities) visible, the society will be better positioned to take into account the impacts of activities that have previously been ignored.

Traditionally, scientists have assessed or analysed components or subsystems of the eco-agri-food system in individual studies. The goal has been to improve the efficiency of each component, based on the assumption that this will also improve the efficiency of the whole system. However, little attention has been paid to connecting the pieces of this puzzle to achieve a comprehensive understanding of what takes place in reality. Indeed, a holistic framework that allows the integration of these pieces into a new, full, picture has thus far been lacking. Using money as the common unit, economists have focused on aspects that can be readily identified, traded and monetized. However, this has left social and environmental impacts along value-chains insufficiently considered or valued, especially if they are financially invisible. By emphasizing evidence-based choices, political decision makers have relied on best estimates and expert knowledge, taking into account only those pieces of the puzzle that are well researched and leaving out much local, traditional and indigenous knowledge. Moreover, the lack of information flow between scientists, practitioners and policy makers exacerbates these shortcomings, contrary to increased emphasis upon evidence-based policy (Pretty *et al.* 2010). Despite evidence of the interconnectedness of challenges across sectors, the current political and scientific incentive structures do not reward integrated approaches that address linkages, time delays and feedback loops, which cut across multiple sectors and disciplines, to seek shared solutions. The consequences, trade-offs and impacts left unaddressed, too frequently work against achieving sustainability in the eco-agri-food system overall.

As population and inequity increase worldwide, critical questions arise regarding how we can produce and distribute food of high nutritional quality to feed a growing global population in a sustainable manner (Foresight 2011). Future policy decisions will increasingly pit multiple domains of ecological sustainability, economic development, and human well-being against one another, but this growing complexity cannot be a cause for inaction. Systems thinking, which focuses on the identification of interrelationships between components, is urgently needed to help us find areas where synergies are possible and where interventions will have the most impact, as well as identify where trade-offs must be recognized and negotiated.

The ambition of the TEEBAgriFood evaluation is to improve the conditions for integrated decision-making for a more sustainable eco-agri-food system. This can only be convincingly done by taking a systems approach to understand how the eco-agri-food system functions within natural and social systems, while at the same time considering cultural narratives and the need for transformational change. To achieve this, the contributions of natural and social capital to the eco-agri-food system need to be made visible. This implies not only focusing on production processes, but also on multiple interactions, feedback loops, and pathways by which the environment and agriculture contribute to human health and well-being. This calls for redoubling efforts to uncover the values of services of nature and roles of social capital not accounted for in the market economy (TEEB 2015) and the full benefits and costs of the eco-agri-food system across all stages of the value chain. We must recognize that the notion of developing a "full" picture is in itself value-laden, critically dependent on what is included (hinging on the nature of knowing and knowledge), what matters to whom, and how we structure, reason, connect and interpret what we see (our underlying perspective or worldview, epistemic beliefs and assumptions). Considering such factors requires discovery of and appreciation for the epistemological views of different social actors, which are inherently value-laden, in order to form a common ground for cultural changes.

The health of our planet and its population depends on bringing together all components of the eco-agri-food system for study and decision-making within an integrated framework. We need a framework where we can understand that *dzud*[1] in Mongolia, protectionism in Europe, political change in the U.S., corporate take-

1 A Mongolian term for summer drought followed by a severe winter, generally causing serious loss of livestock.

over of family agriculture in Australia, or land grabbing in Africa all affect the quantity and quality of food on global markets, the stability of impoverished states, and the functioning of ecosystems in seemingly unconnected parts of the world. We need a framework that can capture how the increasing demand for red meat in Asia could degrade soils in Australia, lead to extinction of yet-to-be-discovered insects, and contribute to the socio-economic collapse of small rural towns. Globalization has created an interconnected global community. We now need a systems-based framework that can help us connect the dots and understand the relationships across multiple sectors, disciplines and perspectives for improved decision-making. Any framework will have limitations, but the one contained in this report was created with the intent to capture as many factors as possible in order to achieve a more holistic understanding and accurate evaluation of the eco-agri-food system.

Understanding the complexity of the eco-agri-food system and its importance for both the health of people and the planet requires systemic analysis based on a comprehensive evaluation framework. This chapter articulates the need for using systems thinking as a guiding perspective for TEEBAgriFood's development of such an Evaluation Framework.

While the empirical evidence of the challenges faced by the eco-agri-food system and the consequences of failing to take a systems view are elaborated in Chapter 3, Chapter 4, and Chapter 5, this chapter explores the role of systems thinking in achieving a more sustainable eco-agri-food system, by lending conceptual support for the development and application of the TEEBAgriFood Evaluation Framework (Chapter 6, Chapter 7 and Chapter 8). Going beyond the Framework to explore other building blocks of a theory of change and its applications is discussed in Chapter 9 and Chapter 10.

In this chapter, following the introduction, Section 2.2 explains why we need systems-based analytical tools. An eco-agri-food system is more than just a production system. Its multiple dimensions create complex analytical and policy challenges that require inclusive conceptualizations and analytical tools. Section 2.3 introduces what systems thinking has to offer, and explains how a systems approach, including conceptualization, investigation and quantification, can contribute to informed decision-making by integrating the key components of the eco-agri-food system, i.e. their economic, social, health, ecosystem, and environmental dimensions. It also demonstrates the application of a systems approach in understanding the eco-agri-food system and evaluating options for future changes to the system. Finally, Section 2.4 concludes with key messages.

Box 2.1 Case study: pushing the ecosystem beyond its critical safe boundaries in the Argentine Pampas during the 20th century

The Pampas of Argentina are a large and complex sand dune system that formed during the last era of Pleistocene glaciations and later semi-desertic episodes. Humans only colonized the region during the last century, but their action was powerful enough to push the ecosystem beyond its safe operating boundaries and trigger two catastrophic events: one during the first half of the century, and the other during the second half. Deforestation and de-vegetation, over grazing and over cropping plus a non-suitable tillage technology, in interaction with extremely dry and windy conditions of the 1930s and 1940s, caused a large dust-bowl episode that led to severe dust storms, cattle mortality, crop failure, farmer bankruptcy and rural migration (Viglizzo and Frank 2006). During the second half of the century, improved rainfall conditions favoured the conversion of abandoned lands into grazing lands and croplands. At the same time, recurrent episodes of flooding affected the area between 1970 and 2017, more drastically in the highly productive lowlands of the area. The configuration of dunes with respect to slope, and the lack of a suitable infrastructure, impeded water removal and favoured its accumulation. The expansion of the cultivation frontier with annual crops provoked a rapid rise in the water table, which dramatically increased the severity of floods during humid periods. Both ecological collapses during the 20th century were the result of a complex interaction of geological configuration, climate variability and human intervention. Over cropping likely surpassed critical ecological thresholds in the area and this, in turn, triggered both the dust bowl and the flooding events. On the other hand, natural feedback mechanisms activated by such events helped with the stabilization and recovery of the affected lands.

2.2 WHY ARE SYSTEMS-BASED ANALYTICAL APPROACHES NEEDED?

2.2.1 Eco-agri-food systems are more than production systems

Agriculture and food systems have typically been evaluated based on their yield, with much research focusing on increasing productivity, rather than on more holistic, integrative natural resources management (NRM), and even less on equitable food access and nutritional security (IAASTD 2009). Using one-dimensional metrics such as "per hectare productivity" is highly problematic as it ignores the negative consequences (i.e. externalities of individuals' choices/activities and of policies) and the trade-offs across multiple domains of human and planetary wellbeing corresponding to the various dimensions of sustainability. Eco-agri-food system and sustainability challenges are tightly linked (Liu *et al.* 2015); however, these are most often studied in isolation. This isolation is a reason for the failure of food systems to provide healthy diets to the global population, and a major driver of pushing us beyond multiple planetary boundaries (Rockström *et al.* 2009).

The world has experienced an extraordinary growth in crop yield since the 1960s due to investments in crop research and infrastructure, and thanks to market development and government support (Pingali 2014). While human populations more than doubled during 1960-2010, the Green Revolution enabled a threefold increase in the production of cereal crops, with only a 30 per cent increase in cultivated land area (Wik *et al.* 2008). The share of undernourished people decreased from 24 per cent in 1990-91 to 13 per cent by 2012 (FAO 2015; Thorn *et al.* 2016a). However, this singular focus on yields has had important environmental costs. The IPCC estimated that roughly one-fifth of the total anthropogenic emissions of greenhouse gases during the 1990s originated from land use changes (Goldewijk and Ramankutty 2004). The intensification of agriculture has had negative consequences with regard to water availability, soil degradation, and chemical runoff, with impacts beyond the areas cultivated (Burney *et al.* 2010). Part of these externalities have been "internalized" within agriculture as manifested in the slowdown in yield growth observed since the mid-1980s, which can be attributed, in part, to the degradation of the agricultural resource base. But much of the externalities remain unaddressed. These environmental costs are widely recognized as a threat to the long-term sustainability and replication of the Green Revolution success (IAASTD 2009; Webb 2009; Pingali and Rosegrant 1994). Some authors have pointed out that the environmental consequences were not caused by the Green Revolution technology *per se*, but rather by the policy environment that promoted overuse of inputs and the injudicious expansion of cultivation into areas that could not sustain high levels of intensification (Pingali 2014). Seppelt *et al.* (2014) show that the peak-rate years (defined as the year of maximum resource appropriation rate) for many of the world's major resources are synchronized (i.e., occurring at approximately the same time in the history of human civilization), suggesting that multiple planetary resources have to be managed simultaneously when assessing the likelihood of successful adaptation of the global society to physical scarcity.

The overemphasis on productivity has also imposed significant costs on human health and contributed to inequity. By 2013, several of the top risk factors driving disease globally were related to diet (GBD 2013 Risk Factors Collaborators 2015). Current food systems over-produce products of low nutritional value and even harmful foods such as sugary drinks, driven by political and corporate interests (Mintz 1985; Richardson 2009), while significantly under-producing many beneficial foods such as seeds and nuts, fruits and vegetables, as noted in the Global Burden of Disease report (GBD 2013 Risk Factors Collaborators 2015).

In addition to the direct food consumption channel, human health can also be negatively affected by the environmentally-mediated impacts of food production. For example, 20 per cent of premature mortality due to air pollution is derived from agricultural activities and biomass burning. Clearing forests for agriculture adds another 5 per cent to these mortality figures (Lelieveld *et al.* 2015). Highly hazardous pesticide use is still widespread across the globe, contributing to a range of health problems such as reduced fertility of male farm workers (Aktar *et al.* 2009; Roeleveld and Bretveld 2008) and increased incidence of fetal conditions and perinatal death (e.g. Maertens 2017; Regidor *et al.* 2004; Taha and Gray. 1993). Negatu *et al.* (2017) found that the expansion of commercial farming in the last decade in Ethiopia has led to a 6- to 13-fold increase in the use of pesticides, which has had an adverse impact on the respiratory health of workers exposed to these pesticides. In Argentina, recent evidence suggests that herbicides (including glyphosate, adjuvants and the metabolite AMPA) have teratogenic and genotoxic effects on mammals and humans and are linked to diverse pathologies and diseases (e.g. Beuret *et al.* 2005; Avila-Vazquez *et al.* 2017).

Importantly, increasing crop production has not guaranteed increased food security or even availability of nutritious food (Smith 2013). Currently, almost one fourth of total food production is wasted, an amount that could feed four times the number of the hungry people in the world (FAO 2011). Food waste is not just an issue linked to inefficiency; it raises important questions of equity and ethics in the global food system. This is especially problematic in countries where subsistence farming was replaced by intensified commercial farming. For example, Sierra Leone now exports food while people experience hunger locally (IFPRI *et al.* 2012). The food justice movement has pointed out that women farmers and other marginal groups continue to experience land insecurity and lack of access to production resources. The case study presented in **Box 2.2** highlights the increasingly interconnected and systemic nature of a "wicked problem" and the converging issues that support and hinder socio-ecological resilience in agricultural landscapes.

Box 2.2 Case study: the complex reality faced by smallholders farming riverside vegetables in the dry season, Northern Ghana

In the semi-arid Guinea-Savannah zone of Upper West and East region of Northern Ghana, smallholders frequently have to contend with weather fluctuations, climate extremes (Tall *et al.* 2014), and hazards such as flooding, drought and storms (Lopez-Marrero 2010; Barrett 2013). All of these factors present risks to agriculture (Harvey *et al.* 2014), such as failed food and seed stores, crop loss, and infrastructural damage. The region is home to the nation's highest rural population of predominantly Dagaare and Fare-Fare agro-pastoralists (84 per cent in the Upper West) - 28 per cent higher than the rural average of 56 per cent and 8 per cent higher than the national average (FAO 2008). However, the current speed and magnitude of climate change undermines farmers' ability to employ traditional methods to cope with variability (Harvey *et al.* 2014; IFAD 2015). Their vulnerability is exacerbated by the fact that these farmers, like many other smallholders, tend to live in marginal environments (e.g. river banks, slopes or close to industrial lands); depend mostly on rain-fed agriculture; farm small parcels of land; and often lack risk mitigation tools, such as regulated long-term credit, cash reserves, reliable weather forecasts, early warning systems, farming inputs or storage infrastructure. Non-climatic stressors compound this risk, including market price fluctuation, under- or over-utilization of synthetic pesticides and fertilizers, and lack of information about appropriate application of inputs. Other issues include limited availability of organic inputs to boost soil fertility, increasing scarcity of land associated with population growth, and lack of labour due to worker migration to Southern urban centres (Tall *et al.* 2014).

Vulnerability is particularly high during the dry season, which typically runs from November – April, when cereal production comes to a halt due to the lack of rainfall, food stocks run low and demand for labour in the south is high (Laube *et al.* 2012). Many agricultural producers "sit idle" during this time, but in recent years, vegetable cultivation has increasingly become an important rural activity (including cultivation of chilli pepper, onion, garden egg, tomato, okra, cabbage, and sweet potato). Vegetables are space efficient, commonly intercropped with other staples crops like cassava, mango and banana, have a high nutritional value and cash crop value, and are growing in demand in urban and rural areas (James *et al.* 2010; Cernansky 2015). Dry season vegetable farming supports biodiversity in terms of landscape configuration and land management (Norfolk *et al.* 2013). Many farmers maintain the landscape surrounding the area in cultivation with patches of native trees, thereby increasing species diversity and heterogeneity as compared to monocropped landscapes (Fernandes and Nair 1986). Land management decisions can also benefit on-farm biodiversity. For example, farmers use mulch to retain soil moisture and promote decomposition, which in turn supports below-ground microbial communities. Concurrently, biodiversity benefits dry season vegetable farming. That is, trees surrounding farms house populations of birds and insects, which in turn support crop productivity through pollination and seed dispersal (Jha and Vandermeer 2010). Biodiversity around farms further provide provisioning ecosystem services such as medicinal and aromatic plants and fodder (James *et al.* 2010).

Despite these benefits, expanding dry season vegetable cultivation faces challenges. Current methods of irrigation are labour and time intensive – with farmers spending 4.5 hours per day filling up to 350 handheld buckets to collect water from riverbanks. The river water is reportedly contaminated, given multiple use requirements for washing, limited sanitation, livestock and the influence of upstream dams on turbidity and velocity. Labour productivity is hindered by limited health services, the continued presence of the parasite *Dracunculus medinensis* (guinea worm), and poor filtration and monitoring of water quality. External international drivers, e.g. European agricultural subsidies, are reducing the export markets for smallholder farmers (Laube *et al.* 2012). Concurrently, farmers suggest that changing climatic conditions they have observed, such as higher temperatures and humidity, have strongly influenced pest incidence on crop production (NPAS 2012). Thorn *et al.* (2016b) confirmed this, showing that in hotter, drier climatic conditions, the proportional abundance of ground- and vegetation-dwelling *Hemiptera* increases, particularly the economically damaging Phytophage, *Homoptera auchenorrhyncha cicadellidae,* and there is a greater risk of seed predation due to the presence of more granivores. However, the same factors have led to an observed greater abundance of long-tongued pollinators, from which farmers may benefit due to more efficient pollen dispersal and decomposition.

This case study highlights the increasingly interconnected converging issues that support and hinder socio-ecological resilience in agricultural landscapes. This complexity creates challenges in how best to balance needs in a changing climate. The need for more clarity is evident in current disagreements in national Ghanaian institutions, some of which advocate for more cultivation of vegetables, while others argue against it. To understand what interventions may enhance smallholder adaptive capacity and sustainability of crop production for environmental services, biodiversity and food security, a systems approach that analyses the interrelations between human and non-human systems across temporal and spatial scales is needed. The TEEBAgriFood Evaluation Framework can help by identifying the total range of impacts and externalities for vegetable cultivation in this scenario, helping the actors involved to choose the best-suited means of crop production for these specific circumstances.

2.2.2 The many dimensions of the eco-agri-food system create complex analytical and policy challenges

The eco-agri-food system is dynamic, complex and *multifunctional,* referring to the inescapable interconnectedness of agriculture's different roles and functions (IAASTD 2009). The concept of multifunctionality recognizes agriculture as a multi-output activity producing not only products (including food, feed, fibres, agrofuels, medicinal products and ornamentals), but also human health effects, livelihoods and employment opportunities, environmental services, landscape amenities, and a source of cultural heritages (IAASTD 2009; Robertson *et al.* 2014). An important attribute that underpins agriculture's multifunctionality is biodiversity. Agricultural biodiversity is a key component of farming systems and breeding systems worldwide, and results in nutritious foods that are culturally acceptable and often adapted to local and low-input agricultural systems (see, for example, **Box 2.1**). Biodiversity is also a source of important traits for breeding climate-tolerant, nutritious crops and animal breeds in the future (Bioversity International 2017). This central role of farm and landscape diversification in transforming agricultural and food system has been highlighted in the 2016 International Panel of Experts on Sustainable Food Systems report (IPES-Food 2016).

The multiple dimensions of the eco-agri-food system create complex analytical and policy challenges (EEA 2017). Efforts to alter one aspect of the system (e.g. reducing environmental pressures) will very likely produce impacts elsewhere (e.g. affecting employment, investments and earnings). This can also mean that interventions produce significant unexpected feedback and side effects. In addition, food systems do not operate in isolation from other systems such as those involving energy, mobility, and wider society, which in turn shape the context in which the food system operates. The use of simplified indicators (i.e. productivity per hectare or GDP of the agricultural sector), focused on selected measurable variables, can lead to poor decisions (EEA 2017). Drawing from reviews of empirical evidence, the case studies presented in **Box 2.4** (Argentina), **Box 2.5** (Malawi) and **Box 2.6** (India) demonstrate how agricultural policies affected the many interconnected aspects of economy and society.

Agricultural policy, through its effect on price and availability of food, is known to be an important determinant of health (Pekka *et al.* 2002; Zatonski and Willett 2005; Birt 2007; Jackson *et al.* 2009; Hawkesworth *et al.* 2010; Wallinga 2010; Nugent 2011). However, health has largely been left out of consideration in agricultural policies (Dorward and Dangour 2012; Fields 2004; Hawkesworth *et al.* 2010), and tension between agricultural and nutritional/health policies is commonplace, and not only in the EU (Aguirre *et al.* 2015; Popkin 2011). The 2013 European Common Agricultural Policy reform liberalized the EU sugar market in 2017, abolishing sugar quotas and lowering EU commodity (or wholesale) sugar prices significantly. Scholars and public health research centres had projected that these changes would have the potential to increase sugar consumption (UKCRC-CEDAR 2015), particularly among the lowest socioeconomic groups (Aguirre *et al.* 2015), while causing substantial losses in sugar exporting by African, Caribbean and Pacific countries (Richardson 2009).

Policies that seem reasonable in one sector or for providing a solution to one problem can cause unintended adverse effects on other sectors, or over a longer time horizon or larger spatial scale. For example, in the Nagchu Prefecture of Tibetan Autonomous Region in China, the enforcement of a conservation area with the aim to restore degraded habitat has resulted in the eviction of semi-nomadic pastoralists who have depended for centuries on the land for grazing livestock, with adverse impacts on their livelihoods (Yeh *et al.* 2015).

Encouragement of high-efficiency irrigation can directly reduce the water use per area and the total water use of a given system. However, the reduction of existing costs of purchasing or pumping water affect the economic productivity of water, which can lead to other changes. First, crops that were previously unprofitable or even agronomically unfeasible may become lucrative, increasing the share of water-intensive crops in the overall cropping system, and increasing the average water use per area. Secondly, the overall area planted with crops may expand. This increase in planted area can again lead to an increase in global water use. These system responses to improved technology can create rebound effects, where gains in efficiency are offset by expanded use. In some cases, global consumption may increase overall, in what is known as the Jevons Paradox. The extent to which a system rebounds will depend in large part upon the strength of system feedbacks (the balancing loops) and the new equilibria they create – at what point increased water and pumping costs inhibit further intensification, or depressed prices inhibit further expansion.

These examples show that systems thinking is needed to improve evaluation and impact assessment before policies or technologies are put in place. An analytical framework capable of integrating subsystems and showing connections between them will improve our understanding of the consequences of choices in quantitative and qualitative terms, across the whole eco-agri-food system. This framework will furthermore help to gather the information needed to make better decisions by agents involved across the value chain. Without systems thinking, we will continue to fail to consider the "what ifs". For example, in any theoretical scenario, what would have been the impact of investing in infrastructure, irrigation, extension and research had the government not spent most of its agricultural support budget on subsidies? What would have been the overall societal impact if more government resources had been used to implement ecosystem-based approaches, instead of agro-chemical input subsidies?

Ideology and culture affect how we understand issues around food (Rosin *et al.* 2012a, 2012b). Food is a vital part of community, family and tradition, and encompasses many non-economic dimensions that are important for individuals and society, but it is often evaluated as just another thing to be bought and sold (Rosin *et al.* 2012a; Vivero-Pol 2017). Pretty (2012) called for developing new alternative models of agricultural and food systems that are culturally embedded and meaningful. Such models would put food at the centre of economies and societies, and ensure that food is produced in ways that improve the environmental systems of the planet.

Box 2.3 Case study: genetic diversity and the eco-agri-food system

An essential component of the global eco-agri-food system is the genetic diversity of crops and livestock. These genetic resources, including both the diversity of cultivated varieties as well as the wild relatives of crops ("crop wild relatives") and livestock, are a key form of natural capital, and the conservation and use of agrobiodiversity is essential for the development of a more sustainable and resilient global food system.

In a way, the improved crops we grow are supported by the entire "genepool" of cultivated and wild diversity to which we can turn to mitigate pest epidemics and stressors like climate change through the breeding of new crop varieties. However, the development of improved varieties has at the same time led to a narrowing of crop diversity as farmers abandon traditional varieties, and as wild lands containing crop wild relatives are cleared for development. Without considering the important role of genetic diversity within the eco-agri-food system, we run the risk of disaster.

Nowhere are the dangers of low genetic diversity more pronounced than in the case of the banana, where a single, clonal variety dominates production for the global export market: the Cavendish. Similar to the Gros Michel, an older variety that was almost completely wiped out by a fungus known as the Panama disease (or Fusarium wilt), the Cavendish is currently facing a new fungal disease, Black Sigatoka (Pseudocercospora fijiensis), in addition to a mutated new strain of Fusarium wilt. Currently, banana plantations are sprayed with fungicides up to 45 times on an annual basis (Vargas 2006) at great economic and environmental cost. The wild relatives of the cultivated banana are a valuable source of resistance genes, and have been used to breed cultivars resistant to Black Sigatoka (Wu *et al.* 2016). However, wild banana populations are declining due to the direct and indirect effects of climate change (Emshwiller *et al.* 2015).

To ensure the long-term viability of banana production, crop diversity needs to be maintained. As this is costly and a global public good, the most adequate strategy is to manage on a global scale, through collaboration between countries. This requires that governments invest in conserving crop varieties in genebanks (and in farmers' fields) as well as crop wild relatives in their natural habitats, work to reduce further loss of agricultural diversity, and facilitate the use of these genetic resources. An example of how this can be partially accomplished is the International Musa Germplasm Transit Centre (ITC), home to the world's largest collection of banana varieties, both cultivated and wild. The ITC has distributed thousands of banana samples over the past 30 years to users in more than 100 countries, as its holdings fall under the jurisdiction of the Multilateral System of the International Treaty on Plant Genetic Resources for Food and Agriculture, which was adopted in 2001 and currently includes more than 100 participating countries.

Similar initiatives are undertaken for other crops; notwithstanding, the challenge of eroding genetic diversity remains huge and is exacerbated by the increasing industrialization of agricultural systems (IPES-Food 2016).

Box 2.4 Case study: what constitutes a "successful" model? The case of soybean industrial production in Argentina

In the last three decades, export-driven industrialized farming was promoted by the Argentinian government as the main model of production and as an agricultural development strategy especially in regard to GM soybeans (Pengue 2005; Teubal *et al.* 2008; Delvenne *et al.* 2013; Leguizamón 2014a; b; Torrado 2016). Favourable international market forces and globalization further aided this trend (Harvey 2003, Pengue 2005; Leguizamón 2014a; Cáceres 2015). This neo-extractivist developmental model (Gudynas 2009; 2014) is heavily dependent on modern technologies and inputs in monoculture-dominated large-scale production systems, as well as the extraction of natural resources (Pengue 2005; Teubal 2006; Cáceres 2015).

However, on what terms is the "success" demonstrated in this case understood? Argentina's industrial agriculture model could be understood as successful within the scope of neoliberalism, and as regards a few "winners", namely, large-scale farming and agribusiness corporations. Argentina ranks third in the world in the production and export of GM soybeans with ca. 20 million hectares under production and an output of 56 million metric tons during the 2014/15 season (Torrado 2016). Soybean has become the most important crop in Argentina (Pengue 2005; Aizen *et al.* 2009; Cáceres 2015; Leguizamón 2016; Torrado 2016; Lapegna 2017), with record harvests and profits (Leguizamón 2014a, 2016; Lapegna 2017). The government also benefited tremendously from resulting export tax revenues (Leguizamón 2014a, 2016; Torrado 2016; Lapegna 2017).

However, the benefits of this model become less certain (or negative) when other perspectives and criteria are considered. A large body of studies has documented that neoliberal policies supporting the expansion of industrial agriculture have generated negative environmental and social impacts. Social inequity is clearly evidenced. For instance, the country is producing "food" for over 300 million people but more than 30 per cent of its population (40 million people) lives below national poverty line (García Guerreiro and Wahren 2016). Moreover, industrial agriculture is one of the main drivers of land use change (Zak *et al.* 2004; 2008; Gasparri and de Walroux 2015); displacement of other crops important for domestic consumption (Teubal *et al.* 2005; Aizen *et al.* 2009); deforestation and forest fragmentation (Torrella *et al.* 2011; 2013; Hoyos *et al.* 2013; Piquer-Rodríguez *et al.* 2015); fresh water pollution (Pizarro *et al.* 2016a; b); and reduction of native plant populations and appearance of invasive species (Vila-Aiub *et al.* 2008; Binimelis *et al.* 2009; Martínez-Ghersa 2011; Ferreira *et al.* 2017). As a result of forest loss, production of vital resources such as wood, grass and hay for domestic animals, honey, and fibres have been considerably reduced (Trillo *et al.* 2010; Arias Toledo *et al.* 2014; Leguizamón 2014a), creating substantial negative impacts on subsistence farmers and indigenous people (Cáceres 2015; Leguizamón 2016; Cabrol and Cáceres 2017; Lapegna 2017). In the land rush for industrial crop cultivation (e.g. soybean), violence against indigenous and peasant families for land control escalated (Carrizo and Berger 2012; 2014; Arancibia 2013; Lapegna 2013, 2017; Leguizamón 2014a; b; Berger and Carrizo 2016).

Studies have also documented the negative social-ecological impacts of fumigation, particularly with glyphosate. Even though glyphosate is considered a less toxic alternative for weed control than some of its precursors, its use is controversial as there is increasing evidence of possible profound eco-toxicological effects of this herbicide on the eco-agri-food system (Bourguet and Guillemaud 2016; Cuhra *et al.* 2016). For example, there have been recent reports in Argentina of direct negative glyphosate effects on freshwater phytoplankton, bacterioplankton and periphyton (Peruzzo *et al.* 2008; Vera *et al.* 2010; Pizarro *et al.* 2016a; b); soils, microorganisms and fungi (Druille *et al.* 2013; 2016; Okada *et al.* 2016); invertebrates (Casabé *et al.* 2007; Mugni *et al.* 2011), amphibians (Lajmanovich *et al.* 2003; 2017; Attademo *et al.* 2014; Mariel *et al.* 2014); reptiles (Burella *et al.* 2017) and fish (Ballesteros *et al.* 2017a; b; Bonansea *et al.* 2017). In wild mammals, domestic mammals and humans, recent evidence indicates that the herbicide glyphosate (with adjuvants and the metabolite AMPA) has teratogenic and genotoxic effects and shows associations with diverse pathologies and diseases (Beuret *et al.* 2005; Carrizo and Berger 2012; 2014; Arancibia 2013; Avila-Vazquez *et al.* 2017).

Looking across the multiple tradeoffs derived from the model, Leguizamón (2014a; 2014b; 2016) pointed out a fundamental conflict between the narrative of "success" of the Argentinean GM soybean boom and socio-ecological sustainability. Systemic analysis is needed to evaluate alternative models of the eco-agri-food system, providing a comprehensive picture of performance, while considering different economic, environmental, health, and social indicators.

Box 2.5 Case study: evaluating the impact of fertilizer subsidy policy in Malawi

This case study presents a review of the empirical evidence regarding the impact of an inorganic fertilizer input subsidy program implemented in Malawi between 2005 and 2010. Smallholder farmers dominate agriculture in Malawi and about 70 per cent of the population depends on agriculture for their livelihood, with maize being the major crop (Denning *et al.* 2009). Traditionally, most farmers used little or no inorganic fertilizers due to high costs. Also, before the intervention maize yield response to inorganic fertilizer was low, due to low soil organic matter and poor response of traditional varieties (Ngwira *et al.* 2012). Due to variable maize prices on the market, the purchase of fertilizer input was seen as risky and unattractive (Dorward and Chirwa 2011).

Starting in the 2005/06 growing season, the Malawian government implemented an ambitious program countrywide, which offered subsidized fertilizer and improved maize seeds through a voucher system, with vouchers distributed through district traditional authorities.

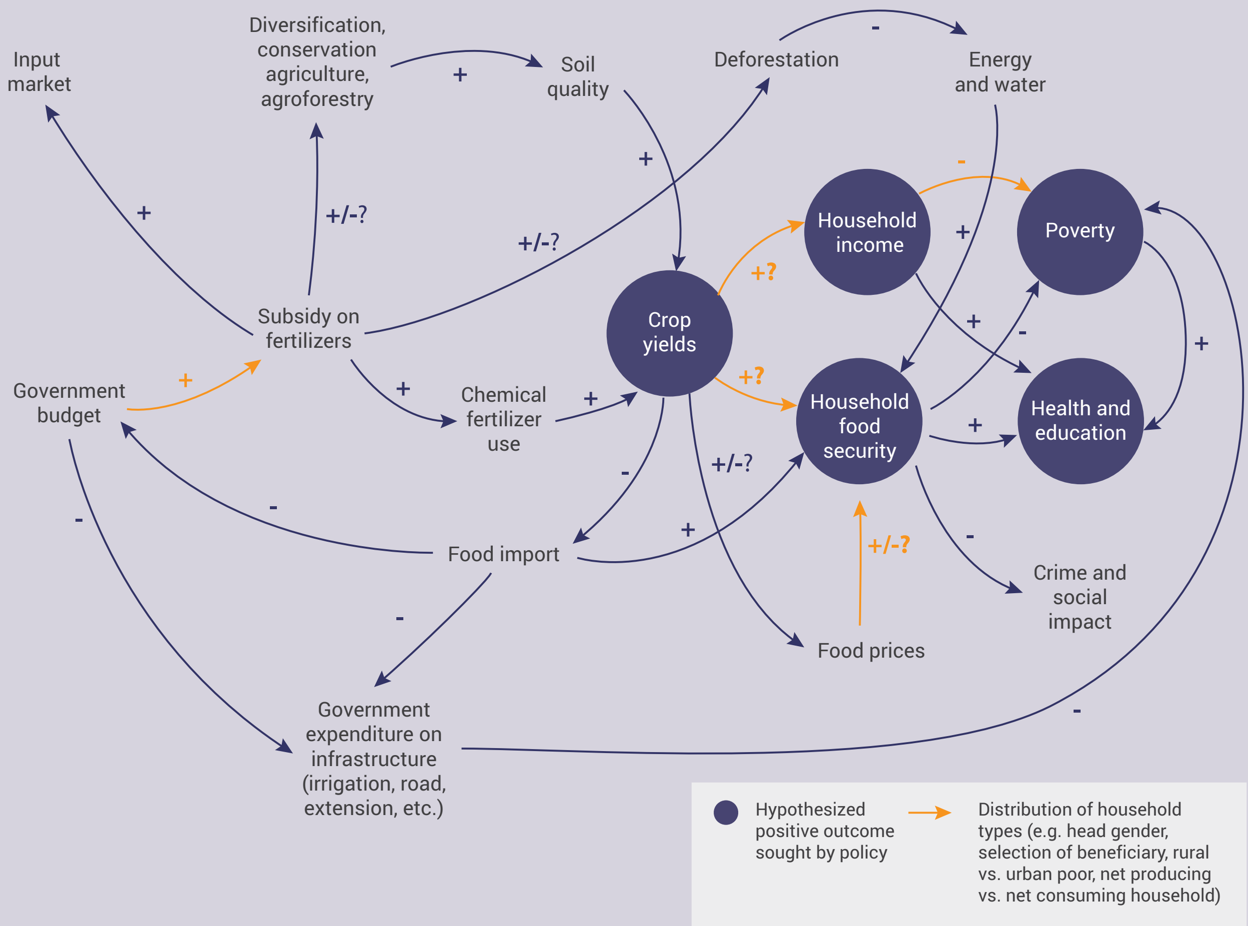
Despite some questions regarding specific figures, there is a consensus that the subsidy program increased agricultural productivity, with bumper harvests in 2005/06 and 2006/07. While this enhanced food security for individual households, the overall impact was uneven. As Sibande *et al.* (2015) found, only the richest 40 per cent of participating households achieved food security as a result of the subsidy programs, with 60 per cent remaining food insecure. It was also found that male-headed households were more likely to be food sufficient compared to female-headed households (Dorward and Chirwa 2011). This gendered effect was partly due to the fact that land ownership was a requirement for participation. In a survey by Holden and Lunduka (2013), 40 per cent of sampled households reported a positive effect on their children's health, with another 65 per cent indicating that children's school attendance improved. However, Lunduka *et al.* (2013)'s review study suggested that the subsidy program might not have improved the overall food security. While national poverty rates decreased by 2.7 per cent, it was mostly the urban poor who benefited from lower food prices (Arndt *et al.* 2016).

At their peak in 2008/09, subsidy costs accounted for 80 per cent of the public budget to agriculture and 16 per cent of the total national budget (Dorward and Chirwa 2011). This had effects on other areas, with reduced budget allocated to infrastructures such as roads and irrigation, as well as to extension and research (Arndt *et al.* 2016).

Importantly, the various studies, which sometimes reached contradictory conclusions (indicated by the "+/-" sign in **Figure 2.1**), show that the impact of such a vast subsidy program is often difficult to assess and quantify (indicated by question marks). This is partly due to differences in timing and methods of data collection. Even when the intended outcome is observed, distributional effects may or may not be positive (the yellow triangle sign in the Figure indicates where such distributional effects may rise). A subsidy program as broad as this one has impacts beyond agricultural practices and food supply. It can improve children's health and school attendance, for instance. Yet, the impact is often heterogeneous, e.g. unevenly divided in terms of benefits between male- and female-headed households, rich and poor households, or urban and rural households. Such a program may inadvertently reinforce existing inequalities. The interdependencies in an eco-agri-food system are complex and trade-offs need to be carefully weighed.

One interesting question is whether redirecting government budgets from simply providing inorganic fertilizer to alternative approaches that are focused more on ecosystem functions and sustainable land management would have helped to avoid some of the documented unintended negative effects while improving productivity in the long run, and what other unanticipated changes might emerge. Uptake of such techniques remains low in Malawi, and outcomes for food security and income are mixed. But their appeal may grow if external driving forces such as climate change put even more pressure on energy supply and crop yields.

Figure 2.1 Mapping evidence of policy impact (Source: authors)



Box 2.6 Case study: energy subsidy and groundwater extraction for irrigation in India

Groundwater irrigation in India covers more than 86 million hectares (ha) out of 192 million ha of gross cropland (GoI 2013). However, agriculture in India is trapped in a complex cycle of groundwater depletion and dependence on energy subsidies (Shah *et al.* 2008). The government subsidizes electricity costs for pumping ground water to encourage greater agricultural productivity, which has encouraged farmers to continue drilling deeper and pumping more. The subsidies are often priced at a flat tariff, if at all, and the groundwater is seldom effectively regulated. As a result, farmers lack monetary incentives to save water or use it efficiently (Narayanamoorthy 2004). The resulting crisis in groundwater resources, especially in northwestern India (Rodell *et al.* 2009), had ripple effects on smallholder farmers, rural communities, and the environment. Despite effort by the government to formulate groundwater regulations and pass state laws, enforcement has largely been ineffective.

Systems thinking is useful for looking at the impact of energy subsidies in India. For instance, several feedback loops exist between the energy subsidies, national imperatives for economic development, food security, the overexploitation of groundwater and consequences for rural livelihoods. At the political-institutional level, energy subsidies have threatened the viability of State Electricity Boards: their capacity is physically stretched by irrigation pumping, and their capacity as organizations is undermined as there are limited incentives for efficiency. Energy subsidies have affected rural populist politics in that political efforts to regulate water are hindered. Proliferation of pumps has also jeopardized the power supply in several states, with implications for regional and urban power services. The energy subsidies have also incentivized farmers to choose water-intensive crops such as rice over less demanding ones, which reinforce the rising demand for irrigation water.

Many responses have arisen in the wake of the socio-ecological challenges associated with energy subsidies in agriculture in India. Most of these include various groundwater management proposals. Some, like the strategy implemented in West Bengal, involve virtually no subsidy on power, because the state has metered all its tubewells and the government now charges farmers at near-commercial rates (Shah *et al.* 2012). Other regions have focused on finding a second-best middle ground that fits the realities of the state level political economy and physical conditions. One such effort is the *Jyotigram* scheme introduced in Gujarat which charges farmers a flat rate tariff, while imposing explicit rationing of high-quality power (Shah *et al.* 2012). Some are focused on improving irrigation efficiency and transitioning away from flood irrigation (Fishman *et al.* 2015). Others have focused on the important role of collective action in order to restrict highly water-consumptive crops where state capacity to control groundwater use is limited (Meinzen-Dick *et al.* 2016). Whether the effort is aimed at correcting distortions rooted in the economic or human behaviour domain, a systems view is necessary to ensure that we look beyond the immediate steps or consequences and consider broader scales and dynamics.

2.2.3 Conceptualizing a sensible operating space for the eco-agri-food system

How can the overall viability and sustainability of any eco-agri-food system be assessed? Much of the current research that attempts to look beyond simple productivity as the only meaningful measure of agricultural production has focused on the biophysical impacts of production systems on the environment. Many studies have looked at how to close the 'yield gap' (i.e. raise yields in less productive systems vis-a-vis industrial agriculture) (Harvey *et al.* 2014; Campbell *et al.* 2014) by examining the impact of conservation strategies on agricultural productivity (Branca *et al.* 2012). It is widely accepted that for human activities to be sustainable, we must respect the ecological constraints on what we can do on and with planet Earth (Clift *et al.* 2017).

Rockström *et al.* (2009a; 2009b) defined 'safe operating space for humanity' in terms of a set of planetary boundaries. The concept has significantly influenced the international discourse on global sustainability (Dearing *et al.* 2014) by using nine interlinked biophysical (hereafter referred to as ecological) boundaries at the planetary scale that global society should remain within, if it is to avoid "disastrous consequences for humanity". Raworth (2012)'s extension of the Planetary Boundary concept to include social objectives, such as health, gender equality, social equality, and jobs, in the context of sustainability policy and practice has produced a heuristic with an explicit focus on the social justice requirements underpinning sustainability (see **Figure 2.2**) (Raworth 2012). Raworth's approach brings planetary boundaries together with social boundaries, creating a safe and just space between the two, in which humanity can thrive. The concept of "safe and just operating spaces" has since been used to guide analysis of regional social-ecological systems in a variety of situations and contexts (for example, in China by Dearing *et al.* (2014), and in coastal Bangladesh as described in **Box 2.7**).

On the one hand, the eco-agri-food system, which is bounded by the same overarching (global) ecological and biophysical constraints and shares the same social foundations as human development, must operate within a "safe and just space for humanity". Defining this space for a given system obviously depends on the values and worldviews held, but systems thinking can play a role in fostering conceptualization and cultural narratives that better appreciate the social and natural foundations of sustainability. On the other hand, the performance of eco-agri-food systems plays a critical role in determining if humanity can thrive within planetary and social boundaries. Systems thinking again can offer conceptual guidance on the methodologies of analysis and governance.

Figure 2.2 The safe and just space for humanity (Source: adapted from Raworth 2012)

Box 2.7 Case study: sustainability of coastal agriculture in Bangladesh: Operationalising safe operating space using social-ecological system dynamics

The safe operating space concept offers a new basis for negotiating trade-offs for sustainable development in the face of growing challenges. Using the safe operating space concept to evaluate the complex dynamics (e.g. feedbacks, nonlinearity) of social-ecological systems, in this case, of agriculture in coastal Bangladesh, involved three research steps: i) analysis and understanding of the co-evolution (drivers, trends, changes points, slow and fast variables) of social-ecological systems involved (Hossain *et al.* 2015; 2016a), ii) unravelling the dynamic relationships (e.g. interactions, feedbacks and nonlinearity) between social and ecological systems (Hossain *et al.* 2016b), and iii) simulation and exploration of the social-ecological system dynamics by generating eight 'what if' scenarios based on well-known challenges (e.g. climate change) and current policy debates (e.g. subsidy withdrawal) (Hossain *et al.* 2017).

Coastal agricultural production doubled in Bangladesh (1.5–3.0 Mt) from 1972 to 2010 due to technological innovation and fertilizer input. The ecosystem, however, has degraded since the 1980s due to increasing temperatures and salinity levels (in both soil and water), rising sea levels and rising ground water levels (Hossain *et al.* 2015, Hossain *et al.* 2016a). Recorded statistics confirm that this area is one of the most vulnerable to climate change (Maplecroft 2010; Ahmed *et al.* 1999) and is also under stress because of land use change, water scarcity, floods, salinity rise and urbanization (Hossain *et al.* 2015; ADB 2005). Projections show that the detrimental effects of climate change in the area are likely to continue, as rice and wheat yields decrease due to temperature increases (MoEF Bangladesh 2005). In such a context, it is highly important to know the proximity of the social-ecological system to tipping points and the chances of stepping outside the safe operating space if a 'perfect storm' of social-ecological failings is to be avoided.

Prior to employing system dynamic modelling to explore the safe operating space in the Bangladeshi delta, we defined the safe operating space in relation to the envelope of variability, environmental limit and impacts on society, assuming that, outside the envelope of variability for crop production, income and GDP, the society will move out from the safe operating space, posing danger to humanity. Eight 'what if' scenarios were formulated based on well-known challenges, current policy debates and stakeholder consultations on the Bangladesh delta in relation to issues such as climate change (debate of 2°C and 3.5°C temperature rise in Paris agreement), sea level rise, withdrawal of subsidy according to World Trade Organization by 2023 and withdrawal of water in the upstream of Ganges delta. Model simulation results for the period 2010s to 2060s revealed that a 3.5°C temperature increase over the period would be dangerous for the social-ecological systems, especially when combined with sea level rise, withdrawal of water and withdrawal of subsidies. Based on the simulated results, we suggest that agricultural development in Bangladesh can stay within the safe operating space by managing feedback (e.g. by reducing production costs) and the "slow" biophysical variables (e.g. by remaining below a 2°C temperature increase), and revising national policies regarding agricultural subsidies. This case study highlights the value of modelling complex social-ecological systems in data scarce regions and demonstrates how we can operationalise sustainability science concepts (e.g. tipping points, limits to adaptation) in real world social-ecological systems.

2.2.4 Currently applied conceptualisations and analytical tools are limiting

'Silo analysis' not only limits a comprehensive understanding of the complexity of the eco-agri-food system, but is also a consequence of the limited availability of data and means to investigate the eco-agri-food system as an integrated complex whole. In this section, we provide some examples of the limitations of the currently applied conceptualizations and analytical tools, which contributed in part to today's challenges with regard to the eco-agri-food system. We also highlight how synergies and coherence can be gained when evidence is generated using concepts and methods that are aligned with systems thinking (Tallis *et al.* 2017).

Treating natural capital using the tools of national income accounting

To understand the limitations of current approaches to assessing the value of natural capital, it is helpful to understand the origins of these approaches. The current system of economic accounting was developed in the 1930s, particularly in the U.S. and U.K. with the creation of the concept of Gross National Product (GNP). GNP was cast as a way to understand "return on investment" that depended on maintaining capital stocks (Solow 1956). This enabled the macro economy to be analysed as if it were one big firm. An important impact of this conceptual development was that it redirected the concerns of economic theory and economic policies away from questions of income distribution towards production, especially through improving efficiency and ensuring the optimal allocation of productive inputs. When employed for long enough, indicators like GNP can ultimately change underlying perceptions of values, becoming valued attributes in their own right (Haider *et al.* 2015) (see the earlier Argentinian case study in **Box 2.1**). Although indicators are formulated to measure what we value, in practice the opposite often happens – we come to value what we measure (Meadows 1998).

An important advancement in income accounting was the realization that capital stock should include the contribution of the services of nature ('natural capital') (Dasgupta and Mäler 2000). In 2012, nearly a century after the rise of GNP as a metric, the UN established the System of Environmental Economic Accounting - Experimental Ecosystem Accounting (SEEA-EEA) (UN *et al.* 2014). Alongside it emerged the concepts of 'green accounting' (Serafy 1996) and 'inclusive wealth' (UNU-IHDP and UNEP 2014).

The *Inclusive Wealth Report* describes four kinds of capital: manufactured or physical, natural, human, and social (UNU-IHDP and UNEP 2014). Each of these capitals is involved in agriculture and all are linked in complex ways. For example, while it may be technologically possible to replace human capital (e.g. farm workers) with manufactured capital (e.g. machinery), this may have negative consequences on social capital (e.g. social networks). As Daly (1996) pointed out, the notion of 'capital' implies that one type of capital can be substituted by another type of capital, a viewpoint that has significant shortcomings. Indeed, the ultimate source of all manufactured capital is the natural world and its essential services are not substitutable.

Georgescu-Roegen (1984) argued that land, labour, and capital are *funds*, not stocks. Funds must be maintained by preserving the conditions that enable them to be perpetuated. Especially in the eco-agri-food system, this seems a more appropriate concept. Ecosystem services such as soil fertility and other vital soil characteristics must be maintained to sustain the output of crops in the long run. Labour (agricultural workers) must also be maintained through health care and the supporting institutions of family and communities. This way of thinking emphasizes the importance of social capital in the economic process. Social capital is particularly important in the eco-agri-food system, whose success depends directly on the supporting functions of family and community (e.g. via the provision of information or appropriate inputs, or labour sharing). Many aspects of industrial agriculture work against sustainability by undermining the social structure that supports farm workers (Lobao and Stofferahn 2008; Goldsmith and Martin 2006) and by drawing down the funds supporting ecosystems services like water quality and availability, pollination and pest control insects, and soil nutrient cycling (Kimbrell 2002).

Awareness is growing that a new way to capture interdependencies and assess trade-offs is required. As Imhoff (2015, p.5) writes in the report on a "Biosphere Smart Agriculture in a True Cost Economy":

"*In the face of a rapidly overheating climate, collapsing fisheries, degraded soil, depleted water resources, vanishing species, and other challenges directly related to agriculture, we can no longer afford to pursue a flawed accounting system.*"

The Millennium Ecosystem Assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB), and the Intergovernmental Platform for Biodiversity and Ecosystem Services (IPBES) are known for their focus on the importance of ecosystems to human well-being and to economic activity. These efforts document the importance of natural capital to economic activity, and the cost of environmental degradation on society. Yet, in view of the magnitude of the continuing deterioration of many ecosystems and social institutions, we must take the concept of biodiversity and ecosystem services and the many dimensions of human wellbeing further by looking at how these issues might be addressed. One of the most salient problems is the difficulty of operationalizing the broad vision of these initiatives; that is, incorporating complexity and interdependence with a systems approach. Because the dependencies and impacts are indirect, interconnected, and complex, seemingly reasonable sector-based policies can lead to unintended consequences that make the whole system (along with its stakeholders) worse off. A key step is to first broaden our analytical framework to allow for the conceptualization and evaluation of the far-reaching implications of various options to manage the eco-agri-food system, in order to inform decision-making, and to improve the existing standards and guidance (e.g. IFC Environmental and Social Safeguards, EIA and SEA directives of the EU).

Beyond single numeraires for evaluating multi-dimensional challenges

Over the past few decades environmental accounting has matured and standardized. Researchers across disciplines can now refer to a set of common methods to measure nature's services. However, like any accounting methodology, environmental accounting is based on simplifications of reality that affect which variables are included, the numbers produced, and their relevance. In the course of reaching consensus on how to construct natural resource accounts or how to estimate environmental services, conceptual difficulties have been glossed over or ignored entirely. Most importantly, in many empirical applications the ecosystem services narrative reduces the value of nature to merely monetary terms that can be quantified and brought into cost-benefit calculations.

Nature is perceived and valued in starkly different and often conflicting ways, and embracing such diversity can aid transformative practices aiming at sustainable futures (Pascual *et al.* 2017). In the context of eco-agri-food system, food has different meanings to different people, including, for example, calorie production, income generation, ways of living, and cultural heritage. Developed within the context of the IPBES, the inclusive valuation of nature's contributions to people (NCP) aims to improve decision making using a pluralistic approach to recognize the diversity of values (Pascual *et al.* 2017).

Appropriate indicators that reflect the complexity of the eco-agri-food system are needed. Haider *et al.* (2015) proposed four principles to guide researchers and practitioners when looking at complex systems. First, indicators are integral parts of a wider monitoring and management system and they provide the key tool by which different elements of the monitoring and evaluation process can be logically connected as attributes change over time. Second, indicators should be designed and used with a suite of other assessment tools and as a coherent part of a wider monitoring system. Even though the use of a single index can provide information (such as GDP), the complex nature of social-ecological systems means that such an index will never adequately capture measures of sustainability. On the other hand, many environmental monitoring programs combine various types of indicators into uncoordinated simple lists with little hierarchical or interactive structure (Gardner 2010). Indicators can only have relevance to management and decision-making processes within complex systems if they are used in coherent and interactive ways, and in the context of a particular aim or objective. Third, it is essential to understand how different indicators relate to the wider system that is being monitored. Finally, indicators, and the monitoring and management systems to which they are linked, should be designed through a participatory process that involves the key stakeholders who are responsible for or influenced by the system attributes that the sustainability indicators are trying to represent. Participatory approaches to monitoring sustainability are particularly important in developing countries, where engagement in the design and execution of monitoring programs by local stakeholders may empower them to better manage their own resources (Haider *et al.* 2015). Moreover, a participatory approach can also encourage a culture of learning, which is paramount to the success of adaptive management (Cundill and Fabricius 2009).

The limitations of comparative static approaches

"Comparative statics" provide a way to evaluate the effects of a change in policy or a production practice by using two 'snapshots', one before and one after a change. However, there are limits to such comparative static analyses when dealing with dynamic and evolving systems. These types of comparisons are usually made based on the assumption that variables remain constant and will not change in a significant way in the future, i.e. the 'all other things being equal' principle. This assumption is highly problematic when considering complex adaptive systems, which are driven by emergence and characterized by change.

Moreover, a snapshot approach does not look at the dynamic interaction of elements within a system, so it may not be representative of the full effects of a change. Some interdependencies might be poorly captured and others overlooked because they are deemed irrelevant or because their effects only become apparent over the long-term.

The case of genetically modified organisms (GMOs) crops is instructive. As Hakimoct (2016) summarizes:

"*The promise of genetic modification was twofold: By making crops immune to the effects of weed killers and inherently resistant to many pests, they would grow so robustly that they would become indispensable to feeding the world's growing population, while also requiring fewer applications of sprayed pesticides.*"

These claims were based on several studies that seemed to convincingly show that GMOs increased yields, required fewer chemical inputs, and had no adverse effects on human health. GMOs were first allowed in the United States and Canada some 20 years ago, but were subsequently banned in most countries in Europe. These political choices led to an unintentional but useful controlled experiment assessing GMOs effect on production, biodiversity, and human and soil health, amongst other factors. According to Hakimoct (2016), the U.S. and Canada showed no discernible gain in crop yields per acre compared to Western Europe. Another unexpected outcome was that herbicide use increased in the U.S. By comparison, Europe's major producer, France, reduced its use of herbicides and pesticides during the same period. Other unexpected impacts emerged in the social sphere. In India, many studies have recognized the adverse social impacts of GMOs stemming from the inability of smallholder cotton farmers to repay loans, which leads to a loss of autonomy and control over food production. These effects have been associated with farmer suicides, the loss of crop genetic diversity and decline in the number of locally adapted varieties.

The debate about GMOs is not conclusive, in part due to a lack of long-term studies and comprehensive assessments of impacts on ecosystem services, social dynamics, and human health. For example, we lack an understanding of how GMOs affect the long-term evolution of herbicide and insecticide resistance in crops, impact predators and pollinators, affect irrigation needs and seed distribution policies, and how GMOs perform under variable precipitation (Romeu-Dalmau *et al.* 2015). To better understand the effect of GMOs, a systems approach would improve our understanding of the interdependencies and trade-offs involved, and thus the situations, contexts and conditions where GMOs would be appropriate or not.

The limitations of efficiency as policy objective

The goal of efficiency is a central concept in economic policy and in research to improve agricultural production. It is not only an essential part of microeconomic theory, but also a driving force in market economies. Businesses strive to create their products at the lowest possible cost, arguably to avoid wasting scarce resources, but also by externalizing a number of costs linked to the environmental and social impact of their activities. It is largely taken for granted that it is an objective criterion and not a value judgment, but as Bromley (1990) pointed out, efficiency is a value-laden ideology—part of a shared system of meaning and comprehension.

The picture from Tanzania in **Figure 2.3** shows the stark difference between plots planted in industrial monoculture versus smallholder agriculture (<0.5ha) (see **Figure 2.3**). Using measures of efficiency and profitability, the industrial system might look preferable, but what effects are left out? Taking a systems view encourages policy makers to consider a larger spatial and temporal boundary, and to assess the impact of alternatives on a broader set of policy considerations, such as employment of smallholder farmers, destruction of the family farming-based system, loss of local knowledge, impact on bio-diverse multifunctional landscapes, and effects on connectivity, flood buffers, habitats, and personal relationships.

Figure 2.3 Photo showing industrial monoculture alongside smallholder agriculture in Tanzania (Source: Bourne 2009)

As Bromley (1990) pointed out, efficiency is only one possible policy goal with no particular claim to being more important than any other. Efficiency is usually interpreted as 'allocative efficiency', i.e. focusing on allocating productive inputs among alternative uses in order to maximize output. However, this is only one way to define efficiency. In systems thinking the concept encompasses the efficiency of ecosystems functioning, or efficiency in the allocation and preservation of social capital to improve the well-being of society. It should also include the notion of 'adaptive efficiency'[2], where the focus is on practices and processes that will enable a system to adapt to changes. This is a core message from resilience thinking: prepare for the unexpected, for example through diversification, maintenance of redundant resources that can be mobilized quickly, and focusing on (social) learning through on-going experimentation (Folke *et al.* 2010; Walker and Salt 2012).

The limitations of marginal analysis and discounting

Marginal analysis is a key decision-making tool in many businesses. It is the process of identifying the relative benefits and costs of alternative decisions by examining the incremental change in revenue over costs caused by a one-unit change in inputs or outputs. The eco-agri-food system has significant implications for sustainability and equity, and limiting evaluations to the yardstick of 'value addition' does not address important equity and resilience issues (TEEB 2015). Marginal analysis does not capture the cumulative effects of small decisions. Kahn (1966) described the "tyranny of small decisions" as a situation where small, seemingly insignificant decisions accumulate and result in an undesirable long-run outcome. Such situations abound in environmental issues. For example, as noted by Odum (1982), the marshlands along the coast of Massachusetts and Connecticut in the U.S. were reduced by 50 per cent between 1950 and 1970 because of small incremental decisions made by landowners.

Discounting is another thorny issue in economic valuation and one that illustrates the divide between an individual perspective and the perspective of "human society" (Gowdy *et al.* 2010). Ecosystem services that support food production become more important as external inputs increase in cost or become scarcer. Even if individuals demonstrate preference for current over future benefits (i.e. discounting the future), that does not necessarily mean that this is appropriate for social decisions (Quiggin 2008). The question of which time frame to use is also critical. Scenario analysis of diverse plausible futures, established envisioned desirable and undesirable futures, and backcasting are approaches increasingly gaining traction as a planning approach to address possible future trajectories along varied time horizons over decadal periods. This diverts from traditional economic planning of four- to seven-year time horizons.

2 Defined by North (2010) as a society's effectiveness in creating institutions that are productive, stable, fair, and broadly accepted--and, importantly, flexible enough to be changed or replaced in response to political and economic feedback.

2.3 A SYSTEMS APPROACH FOR THE ECO-AGRI-FOOD SYSTEM

2.3.1 Origins and evolution of Systems Thinking

Systems Thinking (ST) is an approach that allows better understanding and forecasting of the outcomes of our decisions, across sectors, economic actors, over time and in space (Probst and Bassi 2014). It places emphasis on the system, made of several interconnected parts, rather than its individual parts. Originating from Systems Theory, ST is transdisciplinary, cutting across social, economic and environmental dimensions. Further, it aims at identifying and understanding the drivers of change as determined and impacted by feedback loops[3], delays and non-linear relationships.

ST supports the integration of information through the explicit representation of causal relations. It uses feedbacks, delays, and non-linearity, three crucial properties of real systems, to describe these relations (Sterman 2000). The strengths of some causal relations are determined, among other factors, by cultural norms. New causal relations may emerge in specific settings, requiring the application of a systems approach customized at the local level. To navigate through complexity, ST supports the identification of the main mechanisms underlying the performance of a system through the creation of a cognitive map, such as the Causal Loop Diagram (CLD), described in more detail in Section 2.3.3.

ST is general in scope, meaning it can be applied to several topics and types of systems, and focuses on the integration of drivers of change across fields. As a result, it builds on other applications of Systems Theory. Examples include systems biology, ecology, and systems engineering.

There are several methodologies and tools that support the implementation of ST. In general, the identification of the components of a system and of the relationships among these components represents the so-called *soft* side of Systems Theory; attempts to quantify these linkages and forecast how their strength might change over time represents the *hard* side of the field (Probst and Bassi 2014).

Both applications have greatly evolved over time, originating from Wiener's (1948) book "Cybernetics" in the homonymous field, Odum's (1960) article titled "Ecological potential and analog circuits for the ecosystem", Forrester's (1961; 1969) publications on industrial and urban dynamics (respectively) in the field of System Dynamics, Lorenz's (1963) work on chaos theory, von Bertalanffy's (1968) work and book titled "General System Theory" in the context of biology, to cite a few examples.

Over time, advances have been made both in systems science (e.g. Complex Adaptive Systems, coined by the Santa Fe Institute) and applications of ST to public policymaking (e.g. The Limits to Growth, published by the Club of Rome (Meadows *et al.* 1972)) and the subsequent expansion of the field of System Dynamics (see Chapter 7).

When seeking to implement ST, the soft side is characterized by seeking to understand and map system complexity. This is achieved through the creation of system maps, also called Causal Loop Diagrams (CLD), Bayesian networks (see **Box 2.8** for an example), and mind maps, to cite a few examples. These approaches, together with additional techniques to harvest expert opinion (e.g. Delphi Analysis), allow for the creation of a shared understanding of how a system works, which in turn helps to identify effective entry points for (human) intervention, such as public policies. When this is done using a participatory approach, it helps bring stakeholders together, creating the required building blocks for the co-creation of a shared and effective theory of change.

The *hard* side of ST is represented by several simulation methodologies and models, as presented in more depth in Chapter 7. These methodologies and models offer different ways of unpacking complexity (UNEP 2014). For instance, models can be bottom-up (e.g. Agent-Based Modelling, systems engineering models, Partial Equilibrium Models) or top-down (e.g. General Equilibrium Models, System Dynamics). Models may focus on the understanding of the behaviour of agents, and how these interact with one another, or on explaining the drivers of structural change in the system. Hybrid approaches also exist, where various models are integrated into nested models, or fully incorporated into an integrated model (Probst and Bassi 2014; UNEP 2011). Overall, we find that the modelling field is rapidly evolving, and there is increasing literature on complex systems and on approaches to tackle complexity. We believe that the TEEB Evaluation Framework, built on ST, can help in both: i) identifying what should be included in modelling exercises, to provide useful inputs to decision making, and ii) determining what models to use (if in isolation or in conjunction with others) and, more importantly, how to interpret their results (according to their strengths and limitations).

In the current report, our perspective embraces the notion (and associated behaviours) of embeddedness within the dynamic flows and cycles of nature, and thereby supports

3 "Feedback is a process whereby an initial cause ripples through a chain of causation ultimately to re-affect itself" (Roberts *et al.* 1983, p.16).

the analysis and understanding of a whole system rather than its parts or subsystems (Meadows 2008; Sterman 2000). Analysing the underlying structure of the system allows for plausible inferences about its past and future behaviour (Coyle 2000), which are useful for policy formulation and evaluation.

2.3.2 Applying Systems Thinking to the eco-agri-food system

TEEBAgriFood makes use of scientific advances in relevant disciplines, and argues for better integration of knowledge across sectors and actors. In addition, the study emphasizes the importance of sharing results of analysis effectively in order to better inform decision-making. We argue that using ST and related tools can help all actors in the eco-agri-food system to better plan for the future. Applications of ST can already be found in many other fields within both the private and public sector; together with an emphasis on Learning Organizations (Senge 1990) we can better understand how socioeconomic and ecological systems, as well as organizations and institutions, learn and evolve over time. The TEEBAgriFood Evaluation Framework is inspired by ST and attempts to capture impacts of production, processing and distribution, and consumption throughout the system, keeping in mind of the drivers and contexts of the eco-agri-food system, and important properties of the system such as dynamics, scales, and feedbacks. By doing so, the Framework can help identifying what should be included in more comprehensive modelling approaches.

The eco-agri-food system involves many components, or subsystems, which interact dynamically and give rise to unpredictable properties that emerge at different levels of organization - so-called emergent properties - which are the essential reason for studying systems in the first place. We are accustomed to dealing with ***complicated systems***, composed of many different parts which interact linearly, and whose behaviour thus follows a precise logic and repeats itself in a patterned way. These complicated systems are therefore predictable. ***Complex systems*** are dominated by dynamics that are very difficult to predict. These dynamics are the result of multiple interactions between variables that do not always follow a regular pattern, and are driven by various feedback loops. As a result, their interplay can lead to unexpected consequences. The rapidly evolving environment in which we live requires responses based on careful analysis of alternative intervention options, especially when multiple and simultaneous challenges emerge. Decisions that do not consider the complex dynamics underlying the true causes of a problem risk unintended consequences or side effects.

Today's challenges are increasingly complex, and it will be necessary to apply systems thinking if we are to improve our abilities to address the challenges. In an analysis of the top 100 questions for global agriculture and food security, Pretty *et al.* (2010) identified a series of interlinked and overarching challenges for this century, grouped into: i) climate change and water, ii) biodiversity and ecosystem services, iii) energy and resilience, iv) social capital and gender, v) governance, power and policy making, vi) food supply chains, and vii) consumption patterns. They demonstrate the intertwining nature of agricultural and food systems, and show that solutions will have to come from more than one sphere of political, technological and economic life (Pretty *et al.* 2010; Pretty 2012).

An improved global food system requires radical change to its organization (Rosin *et al.* 2012a; IPES-Food 2016). In reviewing the literature of recommendations for reconfiguring the global food system, Rosin *et al.* (2012b) highlighted that the transformational recommendations all involve significant shifts in the structure and operation of the global food system. One example of structural change in the model of agriculture called upon by the International Panel of Experts on Sustainable Food Systems is to diversify farms and farming landscapes IPES-Food (2016). The environmental limits of our food-related activities must be respected; the functions of the ecosystems in which food is produced must be maintained; the multiple outputs of agriculture and its multiple roles must be considered. Take conservation for example. The aforementioned recommendation implies a recognition of the multiple and often non-monetary and cultural incentives for conservation in agricultural landscapes of different actors. Changes in food production systems must ensure that the environmental, social, and human health qualities inherent to food production and consumption, including but not limited to economic benefits, are valued and therefore maintained. A radical shift in our treatment of food is called for, both in terms of the values we attach to food, and in our imaginings of more just and flexible systems.

Using systems thinking requires a shift in fundamental beliefs and assumptions that constitute what are referred to as our 'worldviews'. These are essentially intellectual and moral foundations for the way we view and interpret reality. This in turn requires a shift in our beliefs about the nature of knowledge and the processes of knowing. For instance, when it comes to judgments about what constitutes improvements to the way land is farmed, our worldviews reflect our views on the nature of human values, particularly as they relate to ethics and aesthetics (Bawden 2005).

Complexity theorists have long recognized the importance of cultural narratives, what Sahlins (1996) refers to as "cosmologies." These are belief systems so ingrained in language and customs that they are hard to recognize. Researchers are making headway in applying the general principles of systems thinking to a variety of social problems involving sustainability (Newell *et* *al.* 2009; Dyball and Newell 2014), and are moving from focusing solely on individual behaviour to emphasizing the importance of cultural institutions and society's assumptions about which policies are feasible and which are not. Behavioural economists and psychologists have made progress in identifying patterns of individual behaviour relevant to policy formulation. Much more work remains in order to understand how transformation towards sustainability can be triggered and supported by policy at societal level.

Increasingly, various fields of policy and corporate practice recognize the necessity of ST and systems approaches in solving today's interconnected and complex challenges. For instance, the development community is moving toward more comprehensive—or systems level—thinking as it looks at issues of poverty, hunger, and malnutrition (Fan 2016). International development organizations such as UNDP, the World Bank, USAID, CIDA, and Japan International Cooperation Agency have shifted to systems concepts-based (FASID 2010), holistic, and integrated approaches (FHI 360 2016) for the design, delivery and evaluation of development programs. The conservation community is also moving in this direction. The Nature Conservancy (TNC), for example, recently stated that creating "systemic change" (creating or strengthening the social, economic, political, and cultural systems that comprise and sustain a socio-ecological system) should be the focus of interventions (TNC 2016). Furthermore, more cross-sector and cross-disciplinary initiatives are emerging, aiming to promote integrated approaches and collaborative work that breaks silos. Among them, the Bridge Collaborative (TNC 2017) envisions global health, development and environment communities jointly solving today's complex, interconnected challenges, first by recognizing the interconnectedness of the challenges each of the three communities face.

These examples show how ST is increasingly embraced because it takes a holistic view of the world and allows for the discovery of interactions (Röling and Jiggins 1998). While system science has been around for more than six decades, to meaningfully embrace the systems approach requires fundamental changes in the way we view and analyse problems and design solutions, as well as the type of institutions we create and use to do this. The TEEBAgriFood study offers a tool, in the form of an Evaluation Framework, to help us advance towards this type of change.

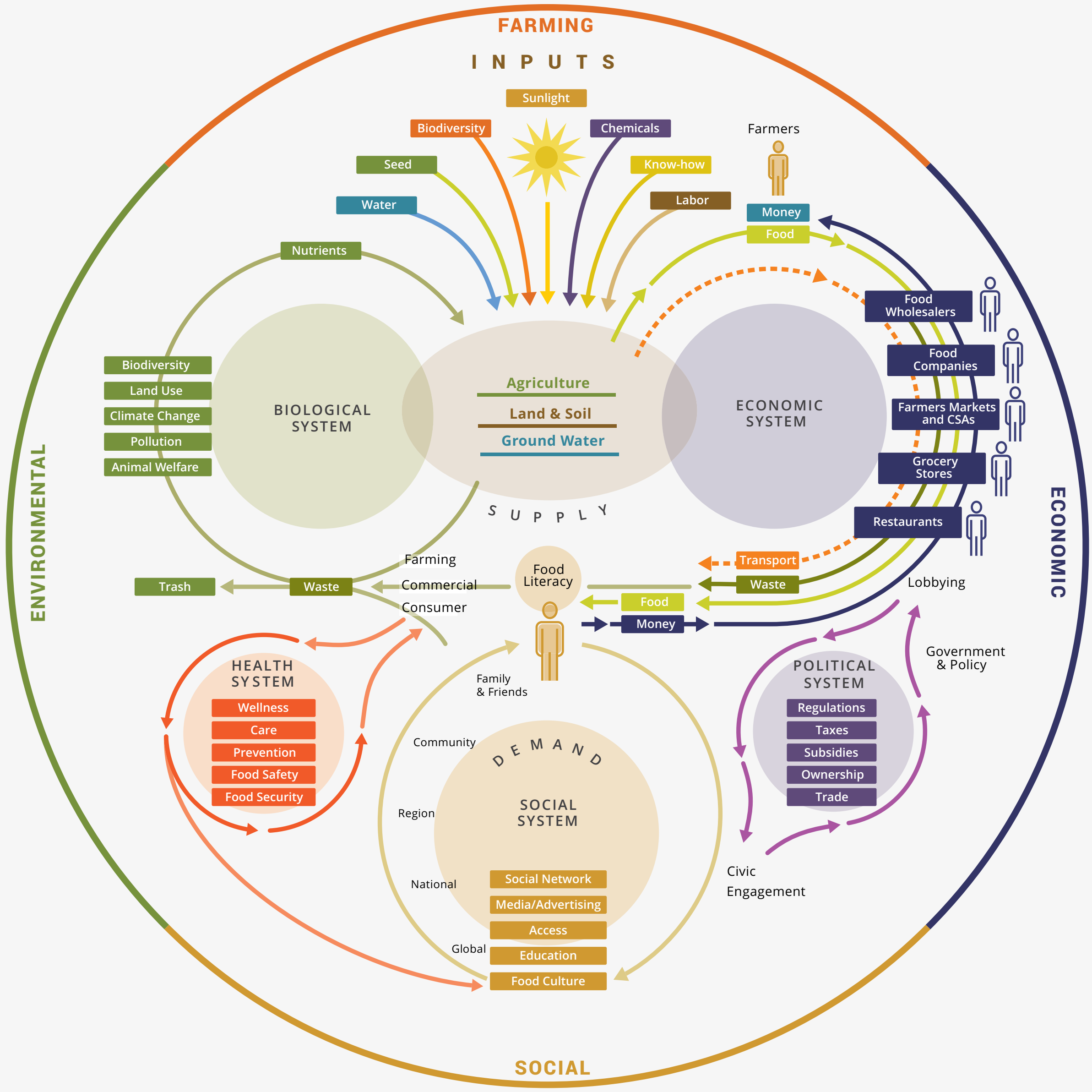
Box 2.8 Case study: Bayesian networks: a useful tool in applying systems thinking?

One of the key challenges in operationalising systems thinking is the integration of interdisciplinary knowledge to provide robust models for decision-making. McVittie *et al.* (2015) used Bayesian Networks (BN) to develop an ecological-economic model to assess the delivery of ecosystem services from riparian zone management on agricultural land. Also known as belief networks (or Bayes nets for short), BN belong to the family of probabilistic graphical models (GMs), which use graphical structures to represent knowledge about an uncertain domain (Ben-Gal 2007). For example, the interface between terrestrial and aquatic ecosystems contributes to the provision of important ecosystem benefits including clean water and reduced flood risk, and is heavily influenced by land use decisions and policy. A participatory workshop gathered scientific and policy stakeholders to explore the linkages across these ecosystems and their ecosystem services. This yielded extremely complex connections that would have presented a considerable modelling challenge. The use of a BN allowed the capture of elements of this complexity whilst focusing on the key interactions between underlying ecosystem processes and the delivery of ecosystem service benefits. An attractive feature of the BN approach is that it can combine quantitative and qualitative data to produce probabilistic outcomes that reflect the uncertainty of complex natural processes.

A second element in developing the BN model was the integration of values for the benefits of the water quality and flood risk services. These values can be monetary or non-monetary and as such can be derived using a variety of approaches (e.g. stated preference valuation, participatory workshops, multi-criteria analysis). The utility or value associated with different outcomes is in turn used to indicate the optimal management option.

Although the BN is a promising interdisciplinary and participatory decision support tool, there remains a need to understand the trade-off between realism, precision and the benefits of developing joint understanding of the decision context (McVittie *et al.* 2015). Important issues such as feedback loops and spatial and temporal factors are also not easily incorporated into BNs.

Figure 2.4 Food systems map that shows how multiple subsystems interact (Source: adapted from the Nourish initiative n.d.)



Systems can be represented in multiple ways. **Figure 2.4**, for example, shows a holistic representation of food systems used by the Nourish initiative. They can also be described verbally, through mathematical equations, or by simulation approaches such as those commonly used in climate modelling and land use analysis (Malczewski 2004). These diverse approaches are used by systems scientists to simulate how systems function and, foremost, to improve our capacity to describe systems, and eventually predict system changes and outcomes caused by interventions.

Figure 2.4 shows material flows within the food system, but also flows of money and knowledge. Importantly, represented by the figures of humans, it shows how many dynamics are driven by individual and societal choices, rather than impersonal 'principles' or 'laws of nature.' Indeed, next to biological, economic and social systems, the political system is drawn separately to highlight its role in the food system. Understanding the food system by only accounting for the economic flows fails to account for other important driving factors.

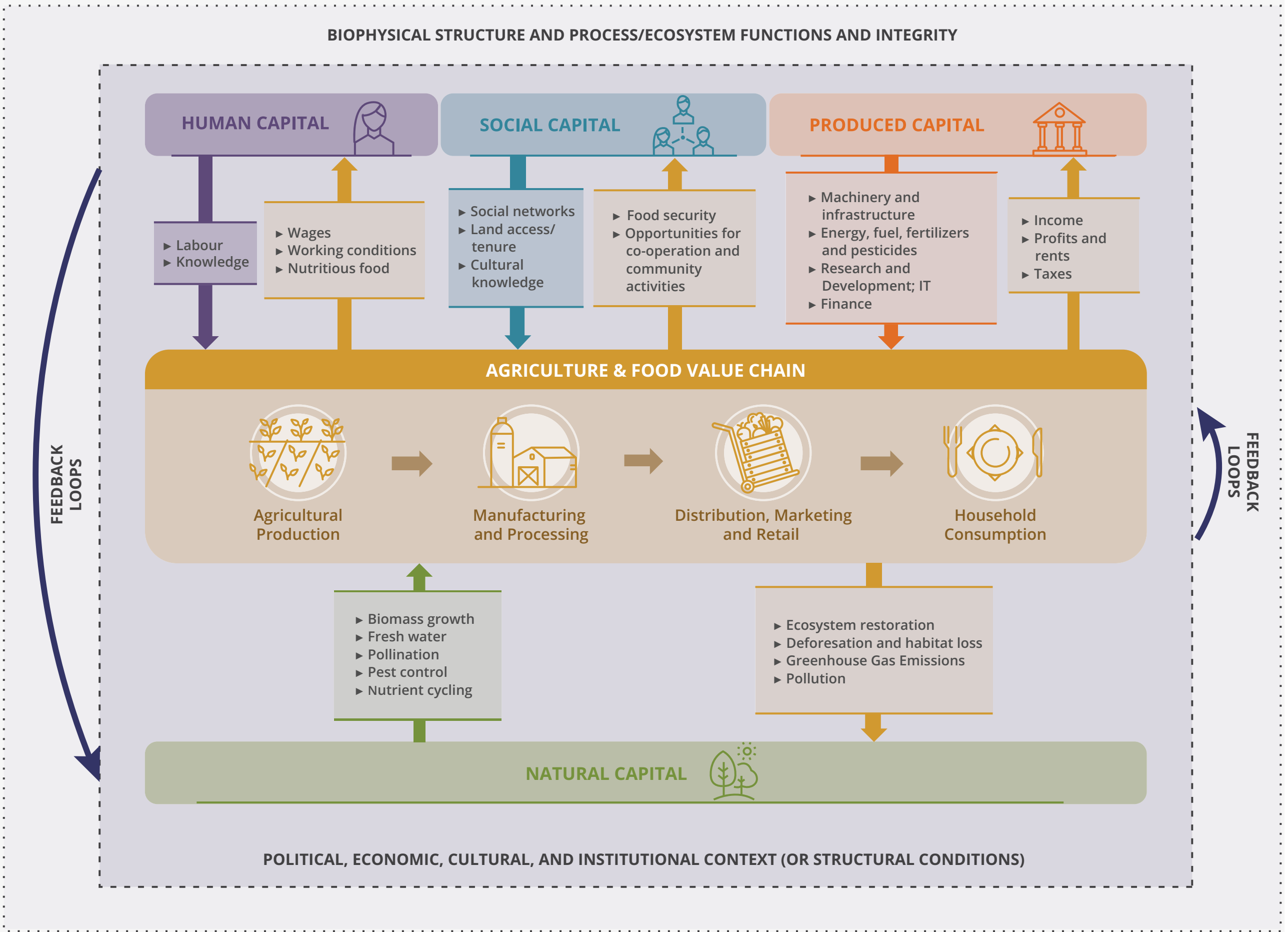
To highlight the fact that many different dimensions are involved in the eco-agri-food system and complex interconnections and feedback loops drive the relation between them, a slightly modified version of the "simplistic" system diagram of an archetypal eco-agri-food system is used in **Figure 2.5**. It illustrates the key components and linkages to be considered when assessing the eco-agri-food system, including the context in which the value chain is embedded, as well as some of the key system features discussed above. These include:

Value chain perspective and its macro contexts

The eco-agri-food system value chain encompasses all actors and activities involved in food production, processing, distribution, and consumption. Within the social and natural subsystems, the stages of an eco-agri-food value chain are tightly intertwined. Demand, production, and distribution of food all form closed loops that are simultaneously and heavily dependent on external influence as well as on internal dynamics. These are represented in **Figure 2.5** by the four stages of the value chain appearing horizontally in the middle of the figure. These stages are connected by two-way arrows showing (simplistically) examples of flows between capital stocks and the value chain in both directions.

Because value chains include activities from food production, postharvest through to consumers, they provide useful lenses for viewing the broader eco-agri-food system and identifying entry points for policies and interventions to improve system performance (Gelli *et al.* 2015). It is essential to understand the broader macro-level context, or enabling environment, within which the value chain operates, including policy and governance, political and economic context, culture, gender, equity, climate and environment (Hawkes *et al.* 2012). Biophysical structure and process both impact and are influenced by the eco-agri-food system; as are ecosystem functions and integrity. Whether these contexts are exogenous or endogenous to the system depends on the time horizon over which decisions are made.

Figure 2.5 Modified high-level 'systems' diagram of an archetypal eco-agri-food system (Source: adapted from authors of Chapter 1)



An inclusive conception of an economy's capital assets

Following the Inclusive Wealth Report (UNU-IHDP and UNEP 2014), the eco-agri-food system relies on the use of different types of capital, including: i) produced capital (roads, buildings, machines, and equipment), ii) human capital (skills, education, health), iii) social capital (or the "networks together with shared norms, values and understandings that facilitate cooperation within or among groups" (Healy and Côté 2001), and iv) natural capital (sub-soil resources, ecosystems, the atmosphere). Other durable assets, such as knowledge, institutions, culture, religion – more broadly considered as social capital - are considered enabling assets, assets that enable the production and allocation of the other three types mentioned before.

These types of capital are represented in **Figure 2.5** by the four outer boxes at the top and bottom of. From these boxes, arrows surround the value chain stages, representing the underpinning role of these capitals for the value chain. The eco-agri-food system not only depends on these capitals for various reasons along the value chain, but also, in turn, impacts these capitals, contributing to positive or negative change in quality, availability, and distribution across spatial and temporal scales.

Analysis of flows: impacts and dependencies on capitals

The flows of supply from each of the four types of capital (natural, social, human and produced) into the activities across the value chain are represented in **Figure 2.5** by vertical arrows 'inputting' toward each value chain stage. Examples of these inputs for the production stage include: i) inputs from natural capital such as energy, land fertility (e.g. nutrients and organic carbon), genetic diversity, water, and pollination services, ii) inputs from produced capital, such as machinery (e.g. tractors), agrochemicals and irrigation infrastructure, iii) inputs from human capital, such as labour, skills, and land management practices, and iv) inputs from social capital, such as knowledge and cultural practices. Among the examples provided above, some are unique inputs that contribute to a single stage of the value chain (e.g. nutrient cycling is used as inflow in the production stage), while others contribute to multiple stages across the value chain (e.g. fresh water is relevant to all stages of the value chain).

As a result of the activities developed in each stage of the value chain, outputs can have a positive or negative impact on society by affecting different types of capitals. These are represented in **Figure 2.5** by vertical arrows 'out-flowing' from the value chain towards the different capital types. Each stage of the value chain generates potential positive outputs, such as wages, food or carbon sequestration that lead to broader societal impacts, such as nutrition and food security (related to crop yield and income), social equity and human health (including nutrition and access to clean water). However, adverse or negative outputs can also arise, such as air and water pollution (e.g. from the use of chemical fertilizers and pesticides), and biodiversity loss (e.g. through habitat loss/fragmentation and agrochemical use); these negative outputs can also have health and social impacts.

System connections: feedback loops and cascading effects

A cascading effect can be noted between inputs and outputs, both within a single value chain stage and across the whole value chain. For instance, all stages require water, which is influenced by various uses (e.g. for irrigation and sanitation) and by the use of chemical inputs and waste (e.g. fertilizers and pesticides). If water is not properly managed, systemic consequences may emerge, where the consumption and contamination of water in one stage may affect all the others (processing and distribution and consumption), and also reach beyond the value chain to affect society.

Feedback loops should be highlighted across the value chain. Impacts on human health may raise awareness among the public about the impacts of unsustainable production, and thus lead to changes in consumer preferences, such as a shift to fair-trade or organic products. Subsequent changes in production practices and processing and distribution standards could improve the quality of food and reduce environmental impacts, resulting in mitigated or reduced health impacts.

A second feedback loop also emerges when considering the full value chain of the eco-agri-food system. The various stages of the value chain share inputs, which are affected by the outputs of all the stages of the eco-agri-food system. Tight interconnections pertain especially to the natural, human and social capital. In fact, with key natural resources being impacted at every stage of the value chain, and being used at each stage (e.g. water quantity and quality, air quality), the performance of the eco-agri-food system is influenced by every activity within its boundaries. Care must be taken when the various stages are dislocated in space, i.e. when natural resources are not shared across the value chain within the same landscape. This is not necessarily an advantage, nor a sign of resilience. Indeed, the lack of direct connections across the stages of the value chain may lead to an overexploitation of natural resources, because this unsustainable use could go unnoticed or unaccounted for a long period of time. It is essential to carefully define the system boundary, both spatially and temporally, to ensure the sustainability of the system.

Actors and their influence

There are many and varied actors influencing and being affected by the eco-agri-food system, which are described in more detail in Chapter 9. These include, among others, governments, NGOs, individuals (different than consumers already considered), financial institutions, other businesses and sectors, and research and academia, which in turn formulate, shape, or implement actions that influence and are affected by the system. These actors determine the performance of the different stages of the value chain, through regulations, financial requirements or engagement policies, campaigns, knowledge and innovations, etc.

2.3.3 An illustrative Causal Loop Diagram of a generic eco-agri-food system model

A causal loop diagram (CLD), i.e. a map of the system, is a way to represent and explore the interconnections between the key indicators in a sector or system. A CLD is thus an integrated map representing the dynamic interplay of different system dimensions and exploring the circular relations or feedbacks between the key elements—the main indicators—that constitute a given system (Probst and Bassi 2014).

CLDs make feedback loops visible, and thus the processes 'whereby an initial cause ripples through a chain of causation ultimately to re-affect itself' (Roberts *et al.* 1983, Probst and Bassi 2014). Two types of feedback loops exist, positive (or reinforcing) feedback loops that amplify change, and negative (or balancing) feedback loops that counter and reduce change. Regardless of the complexity of the system analysed and of the CLD created, only a handful of feedback loops may be responsible for most of a system's behaviour (Probst and Bassi 2014). Thus, if these dominating feedback loops can be identified, entry points for effective intervention, or policy levers, can also be detected.

The creation of a CLD has several purposes. First, it is a means to elicit and integrate a team's ideas, knowledge and opinions. Second, it requires the explicit discussion and defining of the components and boundaries of the analysis. Third, it allows all the stakeholders to achieve basic-to-advanced understanding of the analysed issue's systemic properties (Sterman 2000).

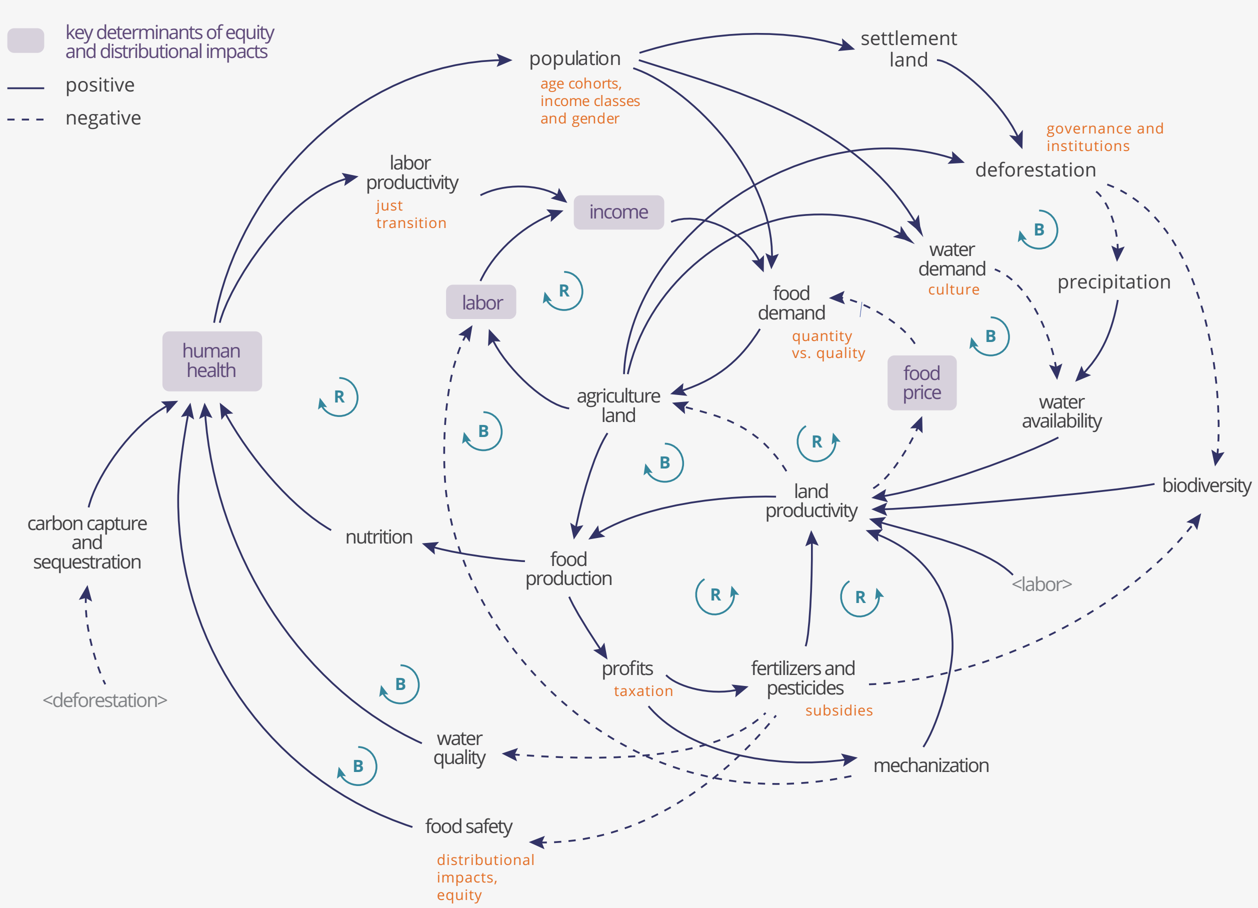
Shared understanding is crucial for solving problems that influence several sectors or areas of influence. When the process of creating a CLD involves broad stakeholder participation, all parties involved need a shared understanding of the factors that generate the problem and those that could lead to a solution. As such, the solution should not be imposed on the system, but should emerge from it. In this context, the role of feedbacks is crucial. It is often the very system we have created that generates the problem, due to external interference or to a faulty design, which shows its limitations as the system grows in size and complexity. In other words, the causes of a problem are often found within the feedback structures of the system.

Figure 2.6 represents a stylized CLD to illustrate some generic relations and system dynamics of the eco-agri-food system. This CLD highlights selected feedback loops that are generally thought to be responsible for the trends observed in the last decades. This CLD does not attempt to comprehensively capture all elements and relationships. It is presented for illustrative purposes to highlight the emphasis on indicators, their interconnections, and the feedback loops that these interconnections form. For instance, we capture the impact of deforestation on water (as an ecosystem service that supports agriculture) as an example of ecosystem service change that resulted from land use choices, but other important elements such as the effects on specific species (currently lumped under biodiversity) are not included here.

Specifically, one of the key drivers of the eco-agri-food system is food demand, which is primarily driven by population and income and also by different industries that convert agricultural production to products beyond food, such as biofuels, additives, livestock feed etc. An increase in demand for these items can lead to the expansion of agriculture land, growth in employment and income, and hence more food demand. This circular relationship represents a positive, or reinforcing (R1) feedback loop, which leads to growth. Further, an expansion of agricultural land would lead to higher food production (all else equal), which would have two main effects. The first one (a) would increase access to food and nutrition, having a positive impact on human health and population (R2) and on labour productivity and income (R3). Two more reinforcing loops are therefore identified, leading to more food demand and land conversion. The second effect (b) emerges over time, with the accumulation of profits and with the improvement of knowledge and technology. This generally leads to an increase in mechanization and the use of fertilizers and pesticides, leading to higher land productivity. This in turn has three main effects, it increases production in terms of higher yield per hectare (R4 and R5); it lowers food prices, which increases food demand (R6); and reduces the amount of land required (B1), all else equal.

At this stage, the eco-agri-food system in **Figure 2.6** is dominated by reinforcing loops, and shows a trend of growth over time. The increase of population and thus demand, leads to the expansion of agricultural land, improved employment and income, as well as increased nutrition, potentially leading to increased population. When this growth is coupled with an increase in land productivity and a reduction in food prices, we generally expect growing demand, production and profits.

Figure 2.6 Illustrative Causal Loop Diagram of a generic eco-agri-food system (Source: authors)



On the other hand, several balancing loops, which constrain growth, also emerge. First, with the adoption of mechanization, labour intensity declines. This leads to higher production and profits for producers, but lowers the potential growth of employment and income (B2), possibly leading to growing inequality. Further, the use of fertilizers and pesticides has negative impacts on water quality (B3) and food safety (B4), two factors that negatively affect human health, and hence labour productivity and population. Finally, the expansion of agricultural land, and the growth of population (and hence the expansion of settlement land) might take place at the expense of forest or vegetation cover. The loss of biodiversity, carbon storage and sequestration with increased carbon emissions can further negatively impact human health (B5), the hydrological cycle, and possibly the productivity of agricultural land (e.g. due to sedimentation, runoff of fertile topsoil or erosion) (B6).

As a result, the growth observed historically (and determined by reinforcing loops) is the cause for the emerging challenges (represented by balancing loops) being faced by the eco-agri-food system: increased reliance on fertilizers and pesticides, more frequent water shortages, an increasing trend of deforestation and growing health impacts (primarily related to the quality of food and nutrition). A silo approach considering individual actors and relying solely on economic indicators would not make visible the emergence of these side effects.

2.4 CONCLUSION

The fact that components or subsystems of the eco-agri-food system are interconnected and interdependent is undisputed. This chapter builds on that observation to make the case for systems thinking as a guide for the conceptualization and analysis of the eco-agri-food system, on which the subsequent chapters of this report offer a concrete attempt to advance.

The many dimensions of the eco-agri-food system create complex analytical and policy challenges. A first step toward a necessary paradigm shift is a re-assessment of how we conceptualise and interpret the problems of the global food sector and how we choose methods to analyse them. To conceptualise what constitutes a sensible operating space for the eco-agri-food system, we draw on the concept of "safe and just operating spaces for humanity" (Rockström *et al.* 2009a; 2009b; Raworth 2012; 2017), emphasizing that we must respect the planetary boundary (e.g. biophysical constraints) while simultaneously addressing social and development objectives (such as health, gender equality, social equality, and jobs). A sustainable eco-agri-food system can only be achieved if the social and environmental dimensions are also taken seriously, in addition to the economic dimension. Silo approaches are limiting our ability to achieve a comprehensive understanding of the interconnected nature and the many challenges we face. We therefore need a holistic framework allowing the integration of well-understood individual pieces into a new, complete picture. Indeed, synergies and coherence can be gained when evidence is generated and used based on concepts and methods aligned with systems thinking.

The shortcomings of current approaches also include the limited availability of data and methods for the analysis of the eco-agri-food system as a complex system. In this chapter we use several examples to explain the limitations of currently applied conceptualizations and analytical tools. We call for expanding the analytical boundary and adopting analytical tools guided by an integrated approach based on systems thinking.

This chapter offers a conceptual representation for the eco-agri-food system, presenting a general overview of the key components and linkages that need to be examined in order to understand the dynamics of the system, as well as the contexts within which the eco-agri-food system value chain is embedded. A stylized Causal Loop Diagram is presented to illustrate some generic relations and system dynamics of the eco-agri-food system. The key elements, dynamics, and relationships will be fleshed out in Chapter 3, Chapter 4 and Chapter 5. The TEEBAgriFood Evaluation Framework presented in Chapter 6 advances on such analysis by attempting to examine all potential impacts and consequences of the respective subsystems.

"Transformability," defined as "the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable," is about shifting development into new pathways and even creating novel ones (Folke 2006, Folke *et al.* 2010, Walker *et al.* 2004). Implementing the TEEBAgriFood Evaluation Framework for the eco-agri-food system puts us in a much better position in the transformative process to understand the full set of impacts of externalities, costs and benefits, particularly on the public goods affected, and thereby identifies what changes would be required for a more balanced and equitable development approach. Further, empowered by systems thinking, the TEEBAgriFood Framework's contribution goes beyond technical analysis by contributing to actively enlisting support for systemic transformations across the stakeholder continuum (see Chapter 9). Systems thinking adopted for the eco-agri-food system can aid forming a common ground for cultural changes through promoting more integrated approaches.

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