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BAE 10th Anniversary papers

Systems Thinking, Mapping and Change in Food and Agriculture

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Abstract. Societal actors across scales and geographies increasingly demand visual applications of systems thinking – the process of understanding and changing the reality of a system by considering its whole set of interdependencies – to address complex problems affecting food and agriculture. Yet, despite the wide offer of systems mapping tools, there is still little guidance for managers, policy-makers, civil society and changemakers in food and agriculture on how to choose, combine and use these tools on the basis of a sufficiently deep understanding of socio-ecological systems. Unfortunately, actors seeking to address complex problems with inadequate understandings of systems often have limited influence on the socio-ecological systems they inhabit, and sometimes even generate unintended negative consequences. Hence, we first review, discuss and exemplify seven key features of systems that should be – but rarely have been – incorporated in strategic decisions in the agri-food sector: interdependency, level-multiplicity, dynamism, path dependency, self-organization, non-linearity and complex causality. Second, on the basis of these features, we propose a collective process to systems mapping that grounds on the notion that the configuration of problems (i.e., how multiple issues entangle with each other) and the configuration of actors (i.e., how multiple actors relate to each other and share resources) represent two sides of the same coin. Third, we provide implications for societal actors - including decision-makers, trainers and facilitators - using systems mapping to trigger or accelerate systems change in five purposive ways: targeting multiple goals; generating ripple effects; mitigating unintended consequences; tackling systemic constraints, and collaborating with unconventional partners.

Keywords: Systems thinking, Causal loop diagrams, value network analysis, wicked problems, agri-food systems, socio-ecological systems.
Jel Codes: Q10, Q19.

1. INTRODUCTION

Societal actors agree, at least in principle, that the complex nature of social and ecological problems affecting food and agriculture – i.e., food

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insecurity, poverty, biodiversity loss, deforestation, water scarcity and global warming among others (Batie, 2008; Dentoni *et al.,* 2012) – requires cross-scale coordination among private strategies, public policies and civic action (Waddock *et al.,* 2015; Bansal *et al.,* 2021; Williams *et al.,* 2021). For example, the European Union's Farm to Fork Strategy (2021), at the heart of the European Green Deal (2021), conceives public-private partnerships as necessary to support farmer entrepreneurship, climate-smart agriculture, food innovation and, ultimately, the resilience of agri-food systems (Manyise and Dentoni, 2021). The new strategy of the Consultative Group on International Agricultural Research (CGIAR, 2021) recognizes that engagement with local communities and the private sector is vital for agricultural research and development (R&D) to address the problems of food insecurity and climate change effectively. These examples demonstrate the need for coordination among market, societal and political actors to collectively agree – or, at least, agree to disagree – on the depth and breadth of changes needed in socio-ecological systems to address these complex problems (Clarke and Crane, 2018; Dentoni *et al.,* 2018).

Unfortunately, these principles of cross-scale coordination among societal, political, and market actors to address socio-ecological problems are still hardly implemented. Clashes among political and economic actors ramp up on how reducing food insecurity, greenhouse gas emissions, and inequality in revenue distributions in the agricultural and food sector (Leakey, 2018; Sovacool, 2018; van der Ploeg, 2020) across several regions of the world. Geopolitical tensions and wars burst worldwide around a lack of coordination in the use and distribution of water, fertile land, energy, and food commodities (Mergulis, 2014; Scheffran, 2020). These interrelated clashes and tensions demonstrate that current initiatives aspiring to trigger, support or accelerate 'systems change' in food and agriculture fail to address socio-ecological problems at their roots unless actors gain a deeper collective understanding of the issues at stake, and of the systems where they are embedded, and how to address them (Gullino *et al.,* 2018; Orr and Donovan, 2018). This mismatch between the principles and the rhetoric of cross-scale, multi-stakeholder collaboration for agri-food systems change (FAO, 2021) and the current reality of increasing tensions and conflicts among the actors involved is strikingly evident and still poorly understood in food and agriculture studies and, more broadly, in the realm of social sciences.

In this paper, we argue that the current failures in cross-scale collaboration to address urgent socio-ecological problems reveal gaps of competencies and processes necessary for actors – especially to those in power positions – to collectively understand the complex socio-ecological problems (Senge and Sterman, 1992; Senge *et al.,* 2007). Based on this argument, we discuss 1) how approaches of *systems thinking* support (or, when not grounded on sufficient understandings of systems, hamper) the development of competencies and processes of cross-scale coordination in addressing complex problems in food and agriculture; and 2) how processes of *systems mapping* contribute to the collective understanding of these socio-ecological problems, and envisioning how to address them. We refer to *systems thinking* as an approach to understanding reality and enacting change by considering the dynamic interactions among multiple interdependent social and ecological agents (Meadows, 2008; Williams *et al.,* 2017). Furthermore, we define *systems mapping* as a process of co-creating visual depictions – for example, diagrams, maps, or sketched models – of a complex system, including its entangled set of relationships and feedback loops among actors and trends (Sedlacko *et al.,* 2014). Systems mapping is often associated to participatory methods for collectively building systems models in group settings (Király *et al.,* 2016; Barbrook-Johnson and Penn, 2021; Wilkinson *et al.,* 2021). Building upon this literature on participatory systems mapping processes, this study focuses mostly on 'what is mapped' (i.e., the map interfaces) to co-create multiple systems maps which, together, support participants in their collective sense-making and envisioning process. In particular, we provide empirical illustrations of how the purposive combination of systems mapping tools helps developing competencies and understandings that have the potential to support *systems change* – that is, societal changes that are deep enough to challenge power structures and broad enough to cut across multiple markets (Dentoni *et al.,* 2017) – in and around food and agriculture.

By connecting systems thinking and systems mapping to the development of individual competencies and collective processes of addressing socio-ecological problems, this paper aims to speak directly to several actors in food and agriculture. First, this delineation of systems thinking features and systems mapping processes inform public and private decision-makers with the power to address socio-ecological problems at scale (Head and Alford, 2015; Banson *et al.,* 2018). These decision-makers need to be accountable for the way they comprehend complex issues before acting on them too precipitously. Second, these systems thinking features and systems mapping processes offer a strategic toolkit for social entrepreneurs, innovators, changemakers and activists seeking to transform food and agriculture from the bottom up (Dentoni *et al.*, 2019). Third, knowledge brokers such as facilitators, trainers and consultants—in applied research institutes (Posthumus *et al.,* 2021), private companies (Monaghan and Gray, 2021) or non-profit organizations (Systemiq, 2020) would benefit from reflection on connecting systems thinking to systems mapping practices and envisioning systems change with more depth and awareness. Finally, systems thinking and mapping provide an important lens to scholars and educators across disciplines to prepare new generations to address complex problems in novel ways (Savaget *et al.,* 2022; Skoll Centre, 2022). These ways are grounded in practices of active listening, reciprocal empathy (Allievi *et al.,* 2021) and collective experimentation (Ferraro *et al.,* 2015), while less driven by static analyses, linear planning and command-and-control agendas that are inherently detached from everyday perceptions of social reality (Meadows, 2001; Walker *et al.,* 2008). While systems thinking and mapping do not mitigate the risk of detachment from social reality (Seelos and Mair, 2018) per se, they offer a lens for societal actors to build collective understandings that are interdisciplinary and transdisciplinary in the way knowledge from multiple actors is shared and integrated.

2. SYSTEMS THINKING IN FOOD AND AGRICULTURE STUDIES: CURRENT LIMITS AND FEATURES

As an approach to understanding reality and enacting change (Meadows, 2008), systems thinking has been applied in a variety of organizational (Senge and Sterman, 1992) and societal contexts (Stroh, 2015) across disciplines (Williams *et al.,* 2017). Nevertheless, with few exceptions (Banson *et al.,* 2015; Orr *et al.,* 2018; Hansen *et al.,* 2020), the agricultural and food studies field is yet to embrace systems thinking with a sufficiently deep understanding of what systems are and what they do. Lacking to do so, we argue, will lead to the generation of literature that, while influential, risks tackling socio-ecological problems without the necessary depth (e.g., Ruben *et al.,* 2018; van Berkum *et al.,* 2018; Borman *et al.,* 2022). We point out three significant limitations of these applications in the current literature on systems thinking in food and agriculture. These include an excessive focus on the exclusive issues of the food sector, persistent linearity, and the implicit assumption that change can and should be planned.

A first limitation of the current literature on systems thinking in food and agriculture entails its *excessive focus exclusively on issues within the agri-food sector* surrounding value chains (e.g., Ruben *et al.,* 2018), hence setting predetermined boundaries for understanding systems (Borman *et al.,* 2022). This excessive focus contradicts the system thinking principle of *understanding the whole* around the strategic variables of interest (Meadows, 2008; Williams *et al.,* 2017). This literature, in particular, considers socio-ecological interactions beyond food value chains essentially as a given context (Ruben *et al.,* 2018; Borman *et al.,* 2022). In doing so, these approaches implicitly or explicitly choose not to understand and address the broader social, cultural, geopolitical, and ecological issues where the food value chains are embedded (Orr *et al.,* 2019). Systems mapping exercises stemming from this excessive focus on a sector or geography usually pressure their participants to set the boundaries of their system of interest (Woodhill and Millican, 2023). While setting boundaries allows to give a stronger focus to any sensemaking or decision-making initiative, it comes at remarkable cost: encouraging participants to remain blind to the relationships outside the set boundaries. Although not directly related to agri-food, these relationships may influence what occurs within the agri-food system. 'Elephants in the room' – such as issues of corruption, socio-political tensions, geopolitical competition for natural resources, energy or water crises – may remain outside these boundaries just because they do not directly relate to agri-food. Hence, this way of setting systems boundaries risks to defy the whole reason for using systems thinking.

A second limitation of recent applications of systems thinking in food and agriculture literature involves *persistent linearity*. Persistent linearity refers to the implicit assumption that actions lead to consequences in the system without recognizing that the system itself also triggers and shapes these actions. The claims that policy, managerial and scientific activities lead linearly to outcomes, goals and problem-solving (e.g., van Berkum *et al.,* 2018) do not take into consideration how these problems affect activities and their outcomes on the ground. This results in an incomplete measurement of the activities' impact that can go as far as to be misleading relative to the actual effects on socio-ecological systems. Hence, while superficially referring to 'non-linearity' (van Berkum *et al.,* 2018: 1), this literature involuntarily retains and perpetuates linear approaches to understanding and changing agri-food systems.

A third and final limitation of this literature is the *assumption that change can be planned*. This literature assumes that food systems could transform through "the design, monitoring and evaluation of multi-annual bilateral programs aimed at different outcomes of sector transformation" (Borman *et al.,* 2022: 100591) rather than through processes of emergence. If we take systems thinking seriously, this assumption is problematic as it fails to recognize that processes of change are spontaneous and continuous, from the interactions between actors in a system to the involvement of those not involved in the design of a system. Yet, research on agricultural systems has pointed out since long time that, at best, change processes can be steered to a limited extent (Klerkx *et al*., 2010). This limitation leads in practice to planned outcomes that necessarily and systematically differ from those envisioned in multi-annual strategy or program reports, thereby questioning their predictive power and credibility. It would be more helpful to consider how multi-annual plans interact with unplanned but plausibly impactful interactions between social (Jagustović *et al.,* 2019) and ecological agents (Brunton *et al.,* 2019) in changing agri-food systems (Hinrichs, 2014). In other words, less time dedicated to planning and more time dedicated to understanding and fostering complementarity among change agents would better fit with the principles of systems thinking.

To answer these three limitations of current literature on systems thinking applications in food and agriculture, we start by reviewing seven fundamental features of systems (Cilliers, 2002; Williams *et al.,* 2017). We illustrate each feature through an empirical example relevant to food and agriculture. These seven features are interdependency, level-multiplicity, dynamism, path dependency, self-organization, non-linearity and complex causality (see Table 1, first column). We argue that taken together, these features provide sufficiently deep underpinnings for mapping systems in ways that support participants to address socio-ecological problems in food and agriculture. On the basis of these features, we encourage actors seeking to address complex socio-ecological issues in and around food and agriculture to take the time and effort to *zoom out, zoom in, zoom up, zoom down, zoom forward, zoom backwards, zoom around and zoom aside agri-food systems* (see Table 1, third column). By doing so, actors seeking systemic change will commit their resources to understanding 'the whole' in a way that looks beyond what is seemingly relevant in the short term. The question that remains to be addressed is: how can these seven principles of systems thinking help actors to collectively understand systems and enact systems change without getting lost in complexity? In what follows, we propose a systems mapping process that takes these principles into account to collectively building a shared understanding and vision of socio-ecological systems change.

3. UNDERSTANDING AND ADDRESSING COMPLEX PROBLEMS THROUGH SYSTEMS MAPPING

Systems thinking begins with the idea of general systems theory, by Ludwig von Bertalanffy (1968), defining systems as foundational models of organization between parts that form a cohesive and relational whole. Considering socio-ecological problems in food and agriculture as an interconnected set of multiple issues and actors helps societal actors seeking to address these problems to understand, harness and tackle their complexity (Dentoni *et al.,* 2018; 2021). It does so because, fundamentally, problems and systems are two sides of the same coin (Senge *et al.,* 2007). If we map a complex system both in terms of the interconnected set of issues and actors that it entails, then we can then understand and envision – at least in principle – how a reconfiguration of these actors could address the complex problems entrenched in that system. By disentangling and making sense of these entanglements between actors and issues, then, we are then better equipped to address these complex problems. For example, problems of food insecurity in a city neighborhood or rural area can be described as a large set of interdependent issues causally connected with each other (a *system of issues*). These would be, for example, extreme heat, drought, inflation, poverty, social exclusion or traffic. The problem of food insecurity may indeed be described through this system of issues. On the other side of the coin, these problems can also be described as a large set of interdependent actors connected (or disconnected) and providing (or failing to provide) valuable resources to each other (a *system of actors).* These would be, for example, consumers, retail shops, food transporters, peri-urban farmers, neighborhood associations, the municipality or the local church. Altogether, this system of actors plays a role in the food insecurity problem, either influencing it or being affected by it. Therefore, *understanding and mapping systems of issues and of actors as two sides of the same coin provide a grounded view of a complex problem, that is, an approach that connects the multiple issues with the multiple actors that experience them.*

Understanding the intertwining of systems of issues and systems of actors provides a starting point for envisioning a collective process of systems mapping meant to collectively address a complex problem. Through systems mapping, envisioning the process of systems change becomes concrete as we realize that *we are part of the system of actors entangled with the systems of issues we are tackling*. By purposively changing our actions and interactions alongside others in our system, we change the system of actors that we are part of (see table 1, 'self-organization' principle). In turn, *by purposively altering our system of actors, we also meaningfully shift the system of issues (or complex problems) we seek to address.*

While each actor could individually make sense of and envision a change in their systems of actors and

Table 1. Seven fundamental features of systems: implications for food and agriculture.

Key systems feature	Example in agri-food context	Implication for systems mapping and change in food and agriculture
Interdependency Agents in a system are independent from, yet indirectly connected with, each other. Systems themselves are also independent from, yet indirectly connected with, each other.	Consumers, value chain actors, policy-makers, farmers, plants, animals are all agents in a food system. Within it, they all indirectly relate and influence each other. Furthermore, the food system relates, influences and is influenced by other systems, such as ecological, energy, political, cultural, financial, technological, and education systems.	To understand the present and envision the future of agri-food systems, we must purposively **<u>zoom out</u> beyond food and agricultural issues** and also consider social problems (such as war and conflict, socio-economic inequality gender discrimination, or ethnic biases from) and ecological problems (such as deforestation, greenhouse gas emissions, land, water and energy use and distribution). We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without taking into account the other systems that influence or are influenced by them.
Multi-level Agents are hierarchically configured in sub-systems (e.g., organizations, networks, states) and spatially embedded within geographical systems (e.g., landscapes, basins, natural regions).	A head of state might impose an export ban on a food community, or an agribusiness company board of directors might disinvest in a country, with trickle-down effects on its food system. At the same time, each consumer and farmer make choices that, although at small-scale, influence the same food system from the bottom up, starting from their family, community, farm and landscape.	To understand the present and envision the future of agri-food systems, we must purposively **<u>zoom up</u> to understand power dynamics that hierarchically and spatially shape the issues**. Furthermore, we must purposively **<u>zoom down</u> to understand how agents 'on the ground'** (that is, within the smaller sub-systems, for example households, farms, teams, networks) **are influenced by these issues and, to the extent they can, seek to address them**. We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without asking ourselves key questions about both power dynamics and everyday practices taking place 'on the ground'.
Dynamism Systems that they constitute are in a constant state of flow, as they react to triggers and stimuli from agents within or outside their boundaries.	War between two countries may accelerate an energy crisis that, in turn, accelerates inflation and magnifies food insecurity issues. Increasing droughts in a region may decrease water use in agriculture, hence reducing agricultural productivity and raising food prices.	To understand the present and envision the future of agri-food systems, we must purposively **<u>zoom forward</u> to foresee how agents or sub-systems that currently do not seem to influence food and agricultural issues in the present time may do so, in interaction with other agents and sub-systems, in the future**. We cannot comprehend the issues facing food and agriculture without asking ourselves what are the key factors that might come into play and shape future scenarios.
Path-dependency Agents act and interact, hence (re)configure sub-systems, also on the basis of their past actions and interactions.	Farmers and value chain actors operating in landscapes that experienced past floods, volcano eruptions or pandemics, in conscious or unconscious memory of their lived experience, organize differently than others. Global value chain may reproduce, consciously or unconsciously, dependency and inequality patterns in their socio-economic relationships.	To understand the present and envision the future of agri-food systems, we must purposively **<u>zoom backward</u> to make sense of why some patterns of action and interaction reproduce themselves over time**, and how they evolve in relation to epochal systems changes. We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without understanding the historical factors that reproduce and maintain the configuration of existing systems.
Self-organization As they act and interact, agents constantly change and adapt systems from within.	Grassroots initiatives (such as alternative food networks or local currency communities) often emerge from relationships between farmers and their communities, or between neighbors. Within food companies, intrapreneurs seek to build relationships within and outside their firm boundaries to influence their corporate strategies, hence the system that they perpetuate. Entrepreneurs seek to build networks and develop new markets that disrupt current systems.	To understand the present and envision the future of agri-food systems, we must purposively **<u>zoom in</u> on-going processes of interaction between agents in a system**, even and especially when these take place at a micro- or small-scale. The emergence of these interactions signals that energy is high enough for some agents to start acting in notably different ways than others constituting it. Therefore, focusing on these processes allows to understand the key factors that justify their emergence in the system, and to anticipate the barriers to change or pathways of change that these processes may trigger. We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without monitoring processes of emergence, what moves them, and what constrains them.

Key systems feature	Example in agri-food context	Implication for systems mapping and change in food and agriculture
Non-linearity Agents reciprocally influence each other in a system, so that causes, effects and boundaries of issues cannot be unilaterally identified.	Companies and citizens seeking to reduce food waste in supermarkets, restaurants and households face legislative. logistic and financial constraints in some countries. This generates vicious circles, because legislation, logistics and financial institutions do not adapt to the demands of actors seeking to reduce food waste unless these reach a critical mass. It might take the reaching of a tipping point, for example a legislative reform or a financial agreement made with a company seeking to reduce food waste, to invert this trend from a vicious to a virtuous system.	To understand the present and envision the future of agri-food systems, we must purposively <u>**zoom around**</u> **the issues that affect them, that is, exploring its causes, manifestations and consequences, as well as their interdependent relationships** (that is, how consequences become reinforcing causes, and vice versa). This implies that 'looking for the root causes' (a label often used by some consultancies, companies or public agencies suffering of short-termism) of complex issues is not just useless, but even counter-productive; if we take non-linearity seriously, then issues affecting food and agriculture do not look like trees (with no 'root causes', nor 'branch consequences'), but they rather look like spiny, climbing bushes. We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without asking ourselves how agents and issues in a system are together entangled in vicious or virtuous circles.
Complex causality Multiple agents influence others in a system, so responsibilities of issues cannot be unambiguously attributed.	Multiple causes and agents influence the phenomenon of illegal forms of agricultural labor: farmers' little power in food value chains, the presence of criminal organizations, cultural factors in a community, lack of employment alternatives for the marginalized individuals in a society, and/or the lack of a clear legislation. None of these causes alone explains this phenomenon, nor an agent alone can be pointed as its sole responsible.	To understand the present and envision the future of agri-food systems, we must purposively <u>**zoom aside**</u> **from just one specific agent or cause that may determine an issue, and identify the other multiple agents and causes that may simultaneously drive the same issue.** It might be simpler to blame just one reason, person or organization for an issue, but complex issues just call for a much deeper investigation of its multiple causes. We cannot comprehend the issues facing food and agriculture, nor elaborate collective strategies to address these issues, without striving to understand the multiplicity of factors that simultaneously shape the issue at hand.

issues to address a complex problem that they are facing, this paper focuses on *collective processes of mapping systems and envisioning systems change*. Firstly, because complexity theory (Cilliers *et al.,* 2002; Waddock *et al.,* 2015; Hubeau *et al.,* 2017), underlines that knowledge co-creation and visualization are necessary to understand a complex problem through its multiple facets. Secondly, because systems thinking focuses on understanding both the dynamics between elements of the system as it does on understanding the functioning of the elements themselves (Levy *et al.*, 2018). Knowledge co-creation refers to complementing the experiences, viewpoints, and information available to multiple stakeholders influenced by (or influencing) the problem at hand (Pohl *et al.,* 2010). Knowledge co-visualization involves using tangible interfaces – for example, diagrams, tables, puzzles or models – to envisage how different information and viewpoints might complement each other or clash with each other (Jean *et al.,* 2018). In the context of collectively understanding complex problems, knowledge co-creation and co-visualization systems have been commonly referred to as systems mapping (Sedlacko *et al.,* 2014).

As a way of knowledge co-creation and co-visualization among multiple actors in a system, systems mapping facilitates collectively understanding complex problems and envisioning changes that will address them over time. Systems mapping consists of creating visual, simplified depictions of a system of issues, such as the relationships and feedback loops, actors, and trends. Collective processes of systems mapping, that is, the action of collectively drawing a systems map integrating the knowledge and perspectives of diverse actors, is commonly referred to as group model building (Vennix *et al.,* 1992; Vennix, 1995; Andersen *et al.,* 2007; Rouwette *et al.,* 2002). Hence, while systems mapping could a priori be done individually by just one actor, group model building represents a group-based way of conveying perspectives from multiple participants' perspectives to generate a simplified understanding of a system. On the basis of how participants are recruited and facilitated (see, for example Király *et al.,* 2016, Wilkinson *et al.,* 2021, Barbrook-Johnson and Penn, 2021 and 2022), group model building conveys the multiple participants' views and values in relation to the complex problem that they seek to collectively address (Videira *et al.*, 2009, Videira *et al.*, 2012). Hence, with effective facilitation, group model building provides a collective understanding of a complex problem by the involved participants, including a clear understanding on what they may agree to disagree. This collective understanding, in turn, helps decision-makers to develop and choose pathways that address this complex problem over time.

While this group model building literature (Vennix *et al.* 1992; Vennix 1996) provides insights on why and how to collectively engage diverse actors in systems to understand a complex problem (Videira *et al*., 2009, Videira *et al*., 2012), this paper departs from (and hopefully contribute to) it in two directions. First, we see systems mapping not only as a process of collectively understanding a complex problem but also as a process of collectively realizing how a system of issues and a system of actors reflect two sides of the same coin. This process gives participants a concrete understanding of how they, individually and collectively, relate to the problem. Second, we see systems mapping not only as a process of collectively understanding a complex problem but also as a process of collectively envisioning how to address it. In our view and experience, expanding this group dynamic from a straightforward collective understanding of a system to a collective envisioning of a systems change provides participants with more opportunities to develop their own competencies and appropriate the feeling of empowerment concerning their role within the system. Instead of just providing their knowledge and delegating the envisioning of systems change to analysts and decision-makers, group participants have the chance to reflect and discuss how to intervene in a system collectively and how to do so collaboratively by pooling resources and sharing resources and tasks. Hence, in the next section, we discuss how our specific approach to systems mapping contributes to applications of systems thinking in these two directions.

4. SYSTEMS MAPPING: VISUALIZING COMPLEX PROBLEMS AND SYSTEMS AT THE SAME TIME

We hereby propose a systems mapping process that, in our view and experience (Table 2), helps addressing the discussed limitations of systems thinking applications in current agri-food studies and of group model building approaches to collectively envision changes in a system. We discuss the principles and stages of this proposed process as follows.

4.1. Systems of issues and systems of actors as two sides of the same coin

To apply systems mapping as a way to collectively understand *how problems (as a system of issues) and social systems (as a system of actors) relate to each other*, and to collectively envision *how to address these problems through systemic change*, we propose a process that combines the use of two maps. These are causal loop diagrams and value network maps (Figure 1). These two maps are complementary and can be used iteratively. Causal loop diagrams help to describe and envision how to address complex problems collectively; value network maps help to collectively describe and alter complex social systems in ways that address these problems. Their use reflects, in this practice, the assumption that systems of issues and systems of actors are two sides of the same coin (Senge *et al.,* 2007; Waddock *et al.,* 2015).

This systems mapping process entails that participants collectively and iteratively draw and visualize these two maps to tackle four sets of questions. Specifically, with causal loop diagrams, participants can tackle the following two sets of questions:

1. What are the specific issues that constitute our problem? And how are these specific issues causally related to each other? (*To collectively understand and visualise a complex problem*)
2. What are the specific issues where we, as participants, could intervene? Which activities or interventions could we envision to address our problem? (*To collectively envision how to address the complex problem*)

Iteratively, with value network maps, participants tackle other two sets of questions:

1. Who are the specific actors that are somehow related to our problem, either because they are affected by it, or because they can influence it? How are these actors connected (or perhaps disconnected) to each other in a social system? And which resources do they share (or perhaps do *not* share) through their relationships? (*To collectively understand and visualize the social systems entrenched in the complex problem*)
2. How can we, as participants, contribute to reconfiguring the social system in ways that address our problem? Specifically, how can we build new relationships (or break old relationships) among actors, and with which resources, to do so? *(To collectively envision how to trigger or support systemic change in ways that address the complex problem*).

The iteration between these two maps, and between the sensemaking and the envisioning phases, allows the participants to go back and forth between making sense of the problem; suggesting how to address it; describing the networks of actors involved in the problem; and considering how to reconfigure the network to address it. Of course, participants may not agree on the answers of these questions, hence on the way that systems maps

Table 2. Empirical evidence in testing and adapting systems mapping approaches.

Title (and year)	Participants	Session length	Country (institutions)
Global Center for Food Systems Innovation (2013-2018)	80 policy-makers, development agency officers and researchers	4 hours (causal loop diagrams + value network maps)	Malawi, Southern and Eastern Africa, United States (USAID)
Putting Big Ideas into Practice: Developing Soft Skills for Large Systems Change (2015)	60 junior scholars across life and social sciences	30 hours across five days (causal loop diagrams + value network maps)	Poland, The Netherlands (Pro-Akademia, European Regional Funds)
Nudge Global Impact Challenge on Global Peace, SDGs and Circular Economy (2016-2021)	90 social entrepreneurs, managers, Master students and activists below 30 years old	2-3 hours (causal loop diagrams + value network maps)	The Netherlands (Nudge B-Corporation and Wageningen University)
Entrepreneurship and Innovation in Emerging Economies (2017-2020)	75 Master students in 3 years	30 hours across 10 workshops (causal loop diagrams + value network maps)	Global, The Netherlands (Wageningen University and EU's Comenius program)
Organizing business models for SMAllholder REsilience (OSMARE) project (2017-2020)	120 dairy farmers, seed growers, value chain actors, policy-makers, and researchers.	5 workshops ranging between 2-4 hours (causal loop diagrams + value network maps)	Malawi, Zimbabwe (NWO/WOTRO and CGIAR/CCAFS)
Beyond Fair Trade: Transnational entrepreneurship and partnerships with African Diaspora (2019)	15 researchers, entrepreneurs in the cacao sector, civil society organizations and Master students.	2 hours (causal loop diagrams + value network maps)	Ghana, The Netherlands (Science Shop, Wageningen University)
Food Design and Innovation (2018-2022)	80 Master students	4 hours (causal loop diagrams + value network maps)	Global, Italy (Polytechnic School of Design)
Changing Socio-Ecological Systems at the Theory-Practice Nexus (2021)	75 management researchers, junior scholars, and management practitioners	3 hours of preparation (causal loop diagrams + value network maps) + 1,5 hours of pitch and reflection	Academy of Management (AoM), Organization & Natural Environment (ONE) and Social Issues in Management (SIM) Divisions
Capacity Development for Agricultural Innovation Systems (CDAIS) (2019)	70 life scientists, research managers, facilitators, consultants, value chain actors and entrepreneurs in the fish sector	16 hours across 2 workshops (causal loop diagrams + value network maps)	Ethiopia with the Feed the Future (FtF) Livestock Innovation Lab, Nigeria with the FtF Fish Innovation Lab (USAID)
Entrepreneurship for systems change (2021-) and Organizational behavior and systems change (2021-)	300 Master students (Program Grandes Écoles, PGE + Master of Science) in 1 year	18 hours across 6 workshops (causal loop diagrams + value network maps)	Global, France (Montpellier Business School)
Comprendre et confronter problèmes socio-écologiques complexes (2022-)	25 company managers, entrepreneurs and Master students	6 hours (causal loop diagrams + value network maps)	Global, France (Montpellier Business School in collaboration with Veolia France)
ENcouraging Farmers towards sustainable agri-food SYStems (ENFASYS) project (2022-2026)	25 applied researchers, research managers, consultants, civil society organizations and junior scholars	1,5 hours (causal loop diagrams + value network maps)	Europe, Belgium (European Commission's Horizon 2020 and Farm to Fork Strategy)

should be drawn. They may for example perceive different relationships between issues and actors, give different value to the addressing of different issues, or have different opinions on pathways to address these issues. In any case, mapping their viewpoints helps them to build a clear understanding of their visions, including their complementarities and their possible antagonisms. Hence, as follows, we briefly describe what causal loop diagrams and value network maps are, and how they can be used meaningfully as part of this systems mapping process.

4.2. Mapping systems of issues through causal loop diagrams

Causal loop diagrams graphical representations of assumed interactions between causes and effects of the multiple elements of a complex problem (Sterman 2000). The set of elements of the complex problems are specific issues which, interrelated to each other, form a system of issues. These causal relationships between elements are simply represented on a map with arrows accompanied by a plus sign (+) or a minus sign (-). The plus sign (+) indicates a positive or direct relationship between two elements, i.e., the 'more of this → the more of that'.

Figure 1. Leaflet of systems mapping workshop at Academy of Management 2021.

For example, if participants note that increasing temperatures cause a rise in water demand, they will connect 'temperatures' and 'water demand' with an arrow accompanied by a plus sign (+). Conversely, the minus sign (-) indicates a negative or inverse relationship between two elements, i.e., the 'more of this → the less of that'. For example, an arrow accompanied by a minus sign (-) could indicate the relationship between 'pollution' and 'quality of life'.

Causal loop diagrams serve two main functions in systems mapping. First, by causally connecting multiple pieces of the problem to each other, causal loop diagrams provide an easy way to *identify feedback loops*. Feedback loops are important to understand the patterns that constitute problems. They can be of three types. First, self-balancing feedback loops reinstate stability in a system: for example, heat → (+) → humidity → (-) → rain → (-) → heat means that, in ecological systems, the patterns linking heat, humidity and rain usually help maintaining a state of equilibrium. Second, vicious circles may cause instability in a system: for example, greenhouse gas emissions → (+) → temperatures → (+) → use of air conditioning → (+) → greenhouse gas emissions constitute a pattern that provokes and accelerates disequilibrium in a system (here, please mind that the plus sign does not indicate anything desirable, but simply a direct relationship between two variables!). These vicious circles are often referred to also as 'lock-ins' in a system, because their non-linearity make it difficult to disentangle and address them (Vanloqueren and Baret, 2008; De Herde *et al.*, 2022). Third, virtuous circles may promulgate desirable changes in a system: for example, investment in renewable energies → (+) → renewable energy stocks → (+) → energy savings → (+) → investment in renewable energies. Independently from the desirability of these patterns, both vicious and virtuous circles represent reinforcing mechanisms (Sterman, 2018).

As a second key function, causal loop diagrams also allow participants to collectively identify the underlying factors that perpetuate the occurrence of vicious circles or impede the generation of virtuous circles. These are often called systemic constraints, barriers or bottlenecks that prevent lock-ins from being addressed. Typical examples of barriers emerging from participants in causal loop diagrams involve institutional issues (such as heavy bureaucracy, incoherent public policies, inadequate market regulation, or corruption), cultural issues (such as conservativism or top-down 'command and control' attitudes in organizations), or ecological issues (such as natural disaster risks preventing social agents to invest on a territory). Importantly, these barriers should not be seen as 'root causes' (see Table 1, non-linearity property of systems) because they themselves may be influenced by other factors in the system. Identifying these barriers, as well as the specific lock-ins that they are perpetuating, are important as possible leverage points, that is, 'places to intervene in a system' (Meadows, 1999: 1). This means that places within a complex system where a small shift of one element within the system can produce significant changes within the overall system (Stroh 2015). Participants can collectively assess if and how to remove these barriers to trigger, support or accelerate systemic change processes (e.g., Abson *et al.,* 2017; Dorninger *et al.,* 2020).

Therefore, relative to more sophisticated systems dynamics, causal loop diagrams have the advantage of being '*rich enough* to capture underlying mechanisms, *precise enough* to spot leverage, but also *simple enough* so that most important dynamics clearly stand out' (Vermaak, 2011: 4). While systems dynamics might be challenging when involving participants outside academic contexts (e.g., farmers, policy-makers, managers, or other civil society representatives) because of its use of stocks, flows, internal feedback loops, and time delays (Lie and Rich, 2016), causal loop diagrams allow participants to visualize, discuss and compare their own understandings of the problem rather than just talking about it (Nicolini *et al.,* 2011). This visualization helps participants to express how they understand the complex problem beyond words, and recognize that they may have talked to each other before but not understood each other's views the with the same level of precision and depth.

However, there are two limitations of causal loop diagrams to be aware of: their inherent reductionism and subjectivism. First, while causal loop diagrams take all seven principles of systems (Table 1) into account, all representations of systems (or systems maps) necessarily reduce the complexity of problems relative to the social reality that it seeks to reflect (Seelos and Mair 2018). To address this limitation, the process of developing causal loop diagrams requires a deep understanding of participatory processes such as the involvement of stakeholders holding different positions and viewpoints on the problem and the creation of space and time for their voices to listened, understood, and acted upon (Király *et al.*, 2016; Barbrook-Johnson and Penn, 2021 and 2022). Hence, depending on the heterogeneous values and frames carried and represented by these stakeholders, the causal loop diagrams will evolve on where the mapping of the issues begins (which usually starts from the question: *what is the aspect of the problem that bothers or hurts you the most?*); for example, for some stakeholders, the starting issue might be 'farmers' household livelihoods' or ‘rural communities’ exposure to drought’; for other, it might be ‘industry profitability’ or, for others again, it might be ‘corruption’ or ‘limited policy implementation’. In these processes, of course, participants may strategically emphasize some issues more than others, or manipulate the relationships between issues, to steer the debate towards where their vested interests lay. The same holds for how much to zoom in or zoom out on the problem or, in other words, on how broad or specific the causal loop diagram should become. During a systems mapping workshop with multiple stakeholders in the Malawian dairy industry, one representative of a dairy farmers’ association sighed loudly and stated: *“We could continue mapping the problems even until tomorrow!”* To address this limitation, the use of causal loop diagrams requires systems mapping facilitation with a deep understanding of participatory processes (Király *et al.*, 2016; Barbrook-Johnson and Penn, 2021). In particular, participants naturally tend to focus on what they value and already know, and to be reluctant to map what they value less or are less familiar with. From our experience, finding this balance between zooming in/zooming out on the basis of participants’ values and viewpoints is more challenging, but also more generative, than forcing participants to set systems boundaries (as we already discussed in section 2).

A second limitation of causal loop diagrams as systems mapping tools involve their subjectivism. All representations of systems, including causal loop diagrams, represent social constructions: depending on the role, status, and viewpoint of the participants in the system they seek to understand, their view on the problems at hand will be different, as well as the envisioned future ways to address them (Seelos and Mair, 2018). To address these limitations, it is important for facilitators of systems mapping sessions using causal loop diagrams to make participants aware of them. The key is that participants focus on their own process of learning – in terms of knowledge integration and/or juxtaposition as their different viewpoints get visualized on the causal loop diagrams. For example, in our meeting with the Malawian dairy industry, participants mentioned that they started to see how someone’s problem (e.g., access to medicine of a dairy farmer) ultimately became a problem for another in their system (e.g., the dairy processer lacking milk supply and government extension workers being warned after problems have emerged). In other words, it is the visualization of mental representations of the complex problems that triggers further thinking. In this Malawian case, for example, we started out with mapping challenges experienced by smallholder farmers (Lubberink and Dentoni, 2019), and then complemented with experiences of the other industry stakeholders (the milk company Lilongwe Dairy, ministries, farmers associations and research institutes). The causal loop diagram showed how the issues highlighted by the different stakeholders were interrelated, and not solely ‘owned’ by any of them. The leader of a farmers’ association shared that *“it was helpful to open your mind and thinking process to see the bigger picture and systematically narrow down the problems”*, and *“it actually is a great method I can replicate in future projects and bring back to my organization and share with others. I also think that it is especially valid in the area of sustainability since everything is so interconnected […], so being able to identify those connections is vital”*. Hence, causal loop diagrams allowed farmers and stakeholders from different villages and viewpoints to share, compare, integrate and sometimes juxtapose their views on their challenges concerning the bigger problem they are collectively seeking to tackle. In doing so, they need to remain aware that, rather than an objective representation of social reality, they are ‘just’ generating a useful and functional collective framing of how they see the problems they seek to address.

4.3. Mapping systems of actors through value network maps

We consider value network maps not as a helpful, but as a necessary complement to causal loop diagrams. As systems of issues and systems of actors are two sides of the same coin (see section 4.1). the process of systems mapping that we propose here has the key advantage of linking representations of interconnected issues, represented by causal loop diagrams, with representations of interconnected actors composing a system, which represent value network maps. By definition, value networks encompass webs of relationships between several actors *together with* the resources transferred, exchanged, shared or co-created among them (Allee, 2008); these resources have a subjective value for the related actors, hence the value of those resources may determine the establishment, evolution or ending of a relationship (Allee, 2008). Valuable resources are not only tangible, such as natural resources, commodities or finance, as commonly depicted in traditional supply chain management, but also intangible such as information, knowledge, training, legitimacy, reputation, rules/hierarchy, or rule enforcement.

Hence, by identifying how actors are connected or disconnected in a system, and resources flow or do not flow among them, value network maps provide a graphical representation of the same problems as causal loop diagrams, albeit in terms of the actors that are involved in a problem or affected by its symptoms (Dentoni and Krussmann, 2015; Barzola *et al.,* 2019), thereby supporting actors to intervene in the system. By drawing and interpreting value network maps collectively, participants are called to reflect upon which actors hold responsibility for the problems at hand and how the re-configuring of their relationships and associated resources may generate the systems change necessary to address these problems (Dentoni *et al.*, 2020; Dentoni *et al.*, 2021). Hence, in value network mapping, participants describe and visualize the involved actors based on the issues identified (Figures 1 and 2). Like in causal loop diagrams, they can zoom into specific issues and actors or zoom out to understand more macro-level patterns depending on how they visually integrate or juxtapose their viewpoints. Participants may agree or not with each other on how they perceive actors in value networks to be connected or disconnected, the resources they share, and the implications of their responsibilities on the problem. Hence facilitation according to participatory principles is again recommended (Király *et al.*, 2016; Barbrook-Johnson and Penn, 2021)

However, to see complex problems reflected in value network maps, participants must first draw them and then interpret them. For example, by looking at the map that they draw, participants should ask themselves: *which actors within the system are tightly interconnected with each other, and which resources do they share?* By answering these questions, participants may recognize *power structures* (Battilana and Casciaro, 2021) that may constitute barriers to address the current problems (Dentoni *et al.*, 2020). Depending on the case, these power structures may revolve around information sharing (Vurro *et al.*, 2009), as dominant actors in global commodity supply chains tend to have at the expense of farmers and farmer organizations (Quarmine *et al.,* 2012); or around rules and rules enforcement, as many small producers of Geographical Indications in Europe (Meloni *et al.,* 2019). A second point participants should reflect upon revolves around the question: *which actors within the system are receiving more resources than what they give, and why?* This may reveal *patterns of dependency* within the system. For example, some actors may appear to need to rely upon most of the resources, while providing to others only one or few; for example, consumers may appear as ‘givers’ of funding in exchange for all other resources; while farmers may appear of ‘givers’ of natural capital (and/or commodities, as fruits of their land), while ‘receivers’ of all other resources (Barzola *et al.,* 2019). A final question to address is: *which actors are disconnected from others, and why?* Reflecting on the *modularity* of the system is crucial, in particular, to understand why resources in a system are unequally distributed, and how a reconfiguration of the system may favor more equal distributions (Dentoni *et al.,* 2020). While the assessment of power structures, dependency patterns and resource distributions from value network maps is inherently subjective, participants should ground their interpretations on the visual observation of actor centrality in the networks and on the directionality of the resource flows.

After reflecting upon power, dependence, and modularity issues in the system, participants would benefit from positioning themselves within the value network map they drew. Starting from the premise that – on the basis of the self-organizing principle of systems (Table 1) – all of us are part of a system and constantly molding it with our actions and interactions (Dentoni *et al.,* 2021), participants should add a supplementary question to complete their value network map before envisioning what should be changed in the future: *where are we, as individuals and organizations, in the map?* Picturing ourselves in the value network map incites us to take responsibility (Jones Christensen *et al.,* 2014) for the current status of the system, as we are also giving and receiving valuable resources with others, hence potentially constitute power structures, perpetuate dependency issues, and reinforce modularity. The habit of thinking of ourselves as part of the system, and constantly shaping it, also triggers action competencies (Olsson *et al.,* 2020), that is, the awareness and drive of being personally involved in processes of social-ecological systems change, through interconnected mechanisms of intrapersonal, interpersonal and organizational change.

The experience built during the USAID Feed the Future program supporting the Ethiopian livestock innovation lab (IFPRI, 2019) provides an example of how this reflection took place (Figure 3). The interpretation of the value network maps, associated with the causal loop diagrams, led the participants (local and international animal scientists, veterinarians, local policymakers, and farmer association representatives) to identify the following barriers to systems change: (1) a tightly interrelated network of policy-makers at the national level that do not prioritize investments in livestock/dairy value chains in agricultural and food policies; (2) modularity in value chains between farmers, farmers’ associations, agricultural input providers and agricultural investors, which hampers the widespread adoption of new agricultural technologies; and (3) the financial dependency of academic institutions, seeking to support the livestock policy, from hierarchy and funding from the national government. These interpretations would not have been reached if the focus of the systems mapping without

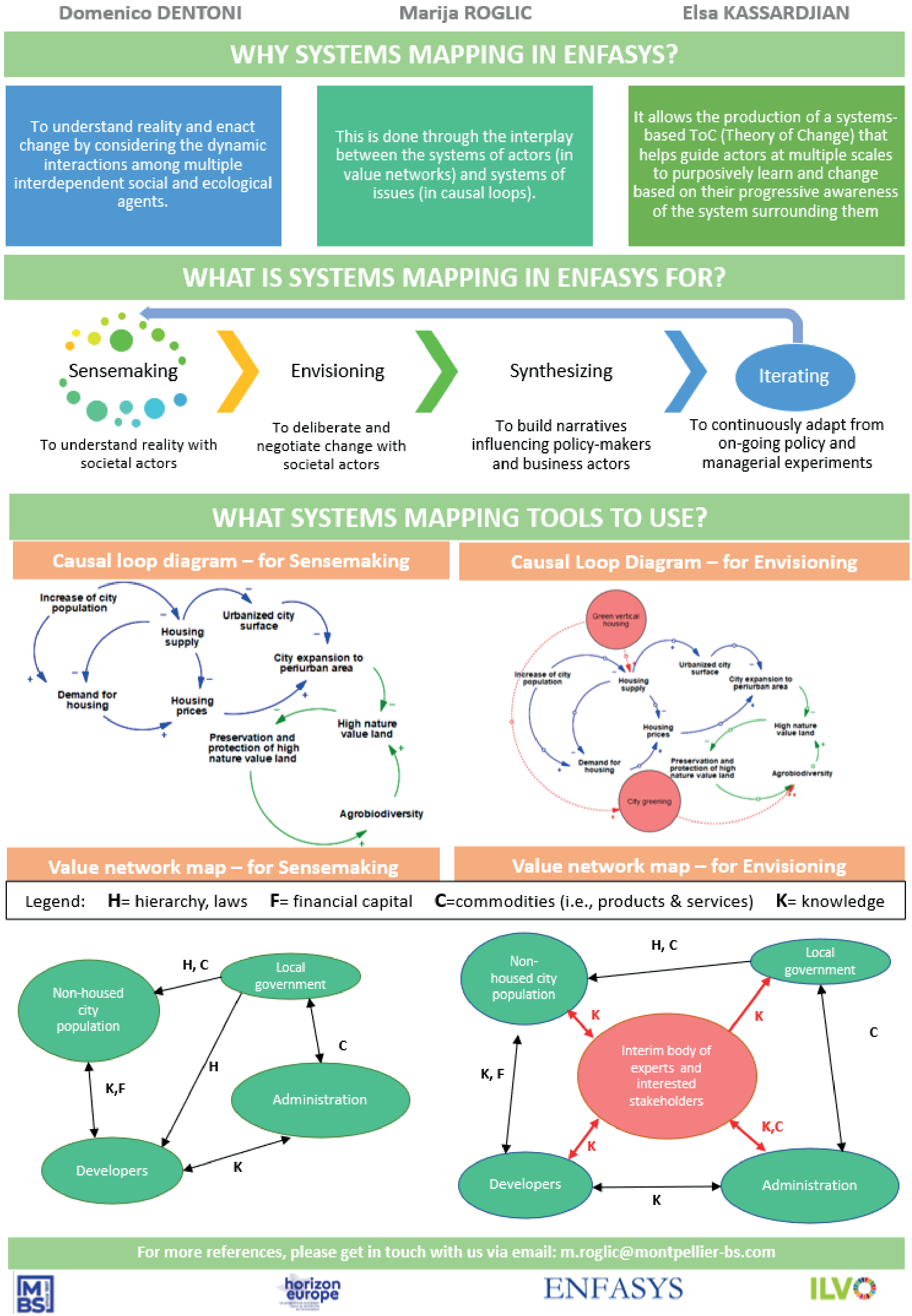


Figure 2. Leaflet of systems mapping approach for ENFASYS project kick-off meeting.

(a) Life scientists, research managers and consultants envision interventions on causal loop diagrams and value network maps during systems mapping workshop in Addis Abeba (2019), as part of the FtF's Livestock Innovation Lab activities funded by USAID. Photo credits: Domenico Dentoni (2019).

(b) Smallholder farmer, ministry of agriculture, dairy processor and health scientist map the complex problems in the dairy industry in Malawi. This was part of the NWO-WOTRO funded OSMARE project. Photo credits: Rob Lubberink (2019).

Figure 3. Participants' groupwork on causal loop diagrams and value network maps.

associating the value network maps to the causal loop diagrams.

This collective process of interpreting value network maps to understand how power structures, patterns of dependence, and modularity in the system reflect and perpetuate complex problems is essential for the next step: envisioning systemic change. As they prepare to move from interpreting of the current system to envisioning a reconfigured system, it is important for participants to consider how to leverage the resources and relationships already in place. This requires a remarkable act of balancing: on the one hand, addressing complex problems may require a comprehensive reconfiguration of the system (which is often referred to as systems transformation, in terms of depth and breadth of systems change; Dentoni *et al.,* 2017); on the other hand, to make the change pragmatically feasible and sensitive to the local context, participants need to also build upon the resources and relationships already in place. This necessary act of balancing is entrepreneurial (Cucchi *et al.,* 2022) in two ways. First, it provides participants with a lens to see complex issues as opportunities to make valuable structural changes to the system they are embedded (Dorado and Ventresca, 2013). Second, this logic of addressing problems by leveraging the relationships and the resources already at hand is inherently effectual (Sarasvathy, 2001). For example, in the Ethiopian livestock innovation lab (IFPRI, 2019), the value network maps helped participants to start thinking about how to change capacity development practices in the livestock industry. This helped them to envision change from short-term trainings and physical infrastructure investments to curriculum development for students in Technical and Vocational Education and Training institutions, in ways that built competencies and incentives to collaborate and create local impact (IFPRI, 2019).

4.4. Envisioning systems change to address complex problems

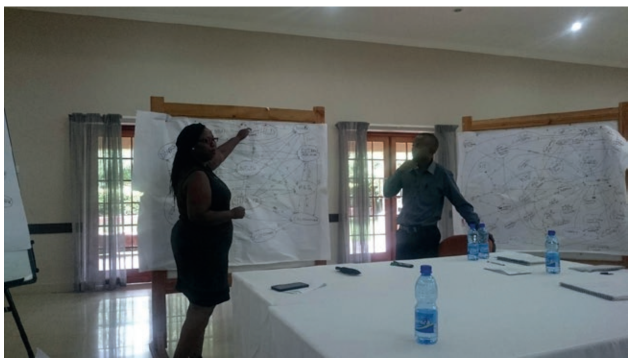
As participants become aware of their reciprocal views of the system and roles in it, and of the problems entrenched in them, they can envision and map action intervention points that collectively address their problems. This collective envisioning process revolves around two iterative stages: First, *envisioning interventions that address the issues using causal loop diagrams*; and, second, *envisioning interventions that alter relationships and distribution of resources among actors in the system using value network maps*. Participants reflect on how to formulate and prioritize interventions that will address prioritized issues by identifying leverage points. Of course, they may also disagree (or agree to disagree) on where and how to intervene; hence facilitation needs to orchestrate this envisioning stage in awareness of participatory principles (Wilkinson *et al.,* 2021). Iteratively, participants deliberate which configurations among actors in the system, connected in new ways or by sharing new resources, will enact the envisioned interventions. Finally, to complete the process, they describe their systems-based theory of change (Wilkinson *et al.,* 2021), that is, how these interventions, enacted through envisioned reconfigurations of their value networks, tackle the complex problems that they seek to address.

The following example from a peri-urban area in southern France (Chaigneau, 2021) illustrates how participants could move from collectively making sense of their system to envisioning its change (Figure 2). Suppose an urban center, facing increased demand for housing, changes its spatial planning to meet the needs of the incoming population and the construction industry, hence spreading the construction zones around the city. This will reduce the peri-urban agricultural land, its agrobiodiversity, and, in the long term, its local agrifood value chain development and resilience to heat waves (Figure 2, upper left quadrant). While citizens exert pressure on the construction industry, the latter sees this as a market opportunity that requires them to collaborate with the municipal administration in charge of spatial planning (Jaroniak, 2022). The municipality is responsible for conveying citizens' demands, setting regulatory constraints and opportunities, and promoting economic opportunities. The central government has the authority and resources to meet the needs of the city population needing housing and regulate the construction industry (Figure 2, bottom left quadrant). To confront these entangled issues of demand for housing, urbanization, agrobiodiversity loss, and climate reduced resilience, participants could envision spatial reconfigurations in their municipal area. This spatial plan would densify the existing residential construction zones by opting for vertical constructions, for instance, residential buildings instead of detached houses, while investing in public infrastructures that support the newly developed areas (Figure 2, upper right quadrant). To enact these spatial planning changes in ways that effectively foster resilience, the municipality will need to align the knowledge from the growing city population councils and representatives of the construction industry, with the regulatory and political constraints posed by the central government. For example, the creation of an interim body of experts and interested stakeholders may be essential to catalyze the existing resources to meet the heterogeneous stakeholder demands and latent needs (Figure 2, bottom right quadrant).

However, the process of moving from systems mapping to envisioning systems change is highly context-specific, hence it may unfold in a vast array of ways. For instance, reconfiguring value networks may require not only envisioning new actions or partnerships but also building coherence between the already existing ones to better complement their efforts in addressing their commonly addressed problems. For example, participants of the workshop in Ethiopia recognized that the day-to-day challenges they face often are characterized by perpetuating vicious circles. The inability of university researchers to organize and advocate for their own needs in an appropriate manner and at the appropriate level. A proposed solution was to strengthen the capacity of the Ethiopian Agricultural Research Council on the livestock research-policy-practice interface (IFPRI, 2019). The council could be capacitated to provide an overview of research demands and research findings in the livestock sector (so as to align research priorities). It also could support livestock researchers in the communication of their research findings for a different audience that can enable or trigger change (e.g., policy influence). Another suggested solution was building researchers' capacity to find their voice and agency, to express their needs appropriately, and to connect them with actors who can play as bridging institutions to create a more comprehensive network (Figures 4 and 5).

Reconfiguring value networks may also imply bringing into the system new actors that before did not have a role and that yet could potentially curb the challenge at hand and support the envisioned intervention. For instance, during the professional development workshop at the Academy of Management conference in 2021 (Figure 1), participants explored a case around food safety

(a) Senior animal scientist from Hawassa University pitches the outcome of his group's causal loop diagrams and value network maps during systems mapping workshop in Addis Abeba (2019), as part of the FtF's Livestock Innovation Lab activities funded by USAID. Photo credits: Domenico Dentoni (2019).



(b) One of the participants in a multi-stakeholder workshop on the dairy industry in Malawi shares the insights retrieved by value network mapping during the systems mapping workshop in Lilongwe, Malawi. This was part of the NWO-WOTRO funded OSMARE project. Photo credits: Rob Lubberink (2019).

Figure 4. Participants' pitches of causal loop diagrams and value network maps.

(a) Seeking to understand lock-ins to systems change in the Ethiopian livestock sector, this group of professionals found a disconnect between skilled lab technicians, vocational education institutes and universities as a leverage point. Hence, they envisioned the constitution of living labs, with the support of international universities and research centers, to address this gap. Photo credits: Domenico Dentoni (2019).

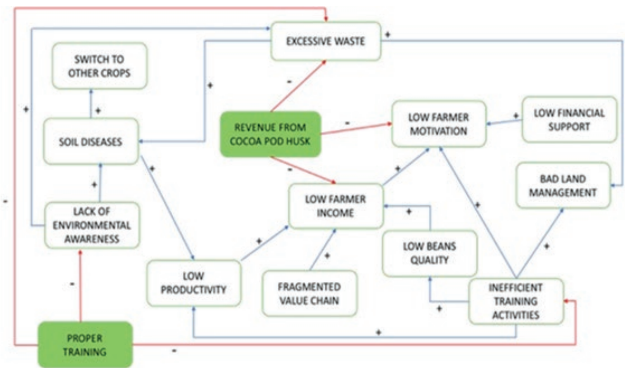
(b) Seeking to understand lock-ins to systems change in the Ethiopian livestock sector, this other group of professionals described how university structures do not provide career incentives for making societal impact. Hence, they envisioned the creation of an Ethiopian Research Council with tasks of coordination and constitution of a 'challenge fund' to change these structures. Photo credits: Domenico Dentoni (2019).

Figure 5. Output of causal loop diagrams and value network maps in workshop.

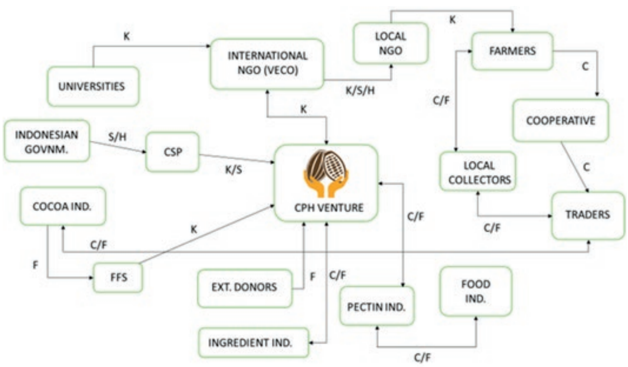
issues in meat markets in Nigeria. After identifying the vicious circles that reproduce food-borne illnesses, participants concluded that informal meat markets' food safety could be improved by enhancing the outreach of training and technology, and accessibility to disinfectant to street vendors. Participants envisioned ministries, businesses, universities, media, and civic associations should complement each other in improving knowledge on healthy handling of vendors and strengthening consumer awareness. Hence, the team envisioned pathways to overcome the current modularity between the health and food subsystems, which are segmented in silos between private and public actors specialized either in food or health; but rarely at their vital nexus. Furthermore, participants envisioned leveraging the role of market associations as a helpful bridge between informal vendors and government agencies, while consumer associations could act as triggers for initiating this change process.

Envisioning change by reconfiguring value networks may also take place in classroom settings for pure competence development purposes. For instance, Master of Science students explored a case around the waste of cocoa pod husks (Figure 6). Based on the local knowledge of one member of the team, triangulated with secondary data collection, students identified the key constraints in the form of causes and consequences of dumping the cocoa pod husks (a waste by-product obtained after the removal of the cocoa beans from the fruit) by smallholder cocoa producers in the Indonesian island of Sulawesi. The group envisioned the creation of a new business venture that, in collaboration with local stakeholders, would support smallholder producers to process the cocoa by-product and convert it into a valuable pectin fiber. Ultimately the pectin material extracted will be sold nationally and internationally. By leveraging the role of unconventional partners, such as local NGOs participants envisioned a pathway that overcomes current power and information asymmetries in the system. In the new set up, the network of local and international NGOs would support smallholder farmers with appropriate training in high-quality pectin extraction processing, activities supervised by local universities specialized in food technology. The business venture value proposition would be therefore intrinsically linked to the farmer's activities through a partnership which reconfigures the network of actors and their associated resources (i.e intellectual property, equipment, expert knowledge) in ways tackle both environmental problems and secure an alternative source of income for smallholder farmers (Figure 6). As a note of caution, this envisioning exercise in the classroom is often detached and sometimes distant from the reality of what is mapped (Seelos and Mair 2018). Hence, trainers and facilitators need to be careful to encourage systems thinking without encouraging 'magical thinking,' that is, the development of unrealistic ideas that are utterly detached from social reality that is mapped (Burton and Muñoz, 2023). To prevent so, they should encourage participants to iterate their idea development with rapid cycles of feedback and experimentation with a variety of locally involved actors.

To sum up, envisioning systems change provides systems mapping participants with concrete strategies and narratives that influence policymakers, business actors and civil society. By continuously adapting the systems maps on the basis of ongoing policy and



(a) This group of Master students at Wageningen University, including one Indonesian student with local networks in this domain, focused on socio-ecological issues in and around the Indonesian cocoa sector. They found that low farmer income and little environmental awareness were critical lock-ins in addressing these issues of rural poverty and environmental degradation. Photo credits: Carlo Cucchi (2017).



(b) Having understood these issues, this group of Master students at Wageningen University, envisioned the creation of a self-sustaining venture to use farmers' cocoa pod husks (otherwise becoming waste) as a source of pectin extraction for the food ingredient industry, with support from the Indonesian government, external donors and international NGOs. Photo credits: Carlo Cucchi (2017).

Figure 6. Example of causal loop diagram (a) and value network map (b) in Master course.

managerial experiments, participants can enact systems change over time. Such an iteration between systems mapping and experimentation on the ground is essential to understand how the participants' understandings and expectations translate in tangible effects when applied in reality. In turn, the experiments implemented on the ground would help participants to adapt and update their systems maps to come up with more grounded ways of envisioning systems change. Hence, this iteration between systems mapping and on-the-ground experimentation will be essential to refine and update (and, if needed, even wholly re-envisioning) the systems-based theory of change that helps guide actors at multiple scales to purposively learn and change based on their progressive awareness of the system surrounding them.

5. TAKING SYSTEMS THINKING SERIOUSLY: IMPLICATIONS FOR AGRI-FOOD SYSTEMS CHANGE

By grounding systems mapping processes, such as those discussed in sections 3 and 4, into a sufficient understanding of systems (articulated in section 2), we argue that societal actors can more effectively trigger and support systems change in directions that address complex socio-ecological problems in food and agriculture. After participating in these systems mapping stages, both public, private and civil society actors can engage in five practices that coherently direct their joint efforts towards envisioning systems change. These are discussed as follows.

5.1. Targeting multiple goals

First of all, we argue that systems mapping processes that combine causal loop diagrams and value network maps support societal actors in collectively envisioning how to address socio-ecological problems while, at the same time, pursuing also their strategic and personal goals. Traditionally, food and agriculture studies have framed the multiple goals of societal actors either as in competition with each other (Grafton *et al.*, 2018) or easy to align under superficial definitions of the triple-bottom line (Detre and Gunderson, 2011). Yet, in food and agriculture studies, we know little how about collaborative practices meant to purposively find a balance between these multiple goals (van Paassen *et al.*, 2022). Our view of systems mapping suggest that societal actors can purposively identify and experiment actions that, through envisioned chains of effects, seek to simultaneously achieve these goals. To target these multiple goals purposively, societal actors need awareness of the multiple cause-effect relationships that constitute the problems they seek to tackle; and the multiple actors that may coherently contribute in addressing these problems. For example, under certain conditions, circular economy solutions for the product of a large multi-national company may simultaneously address climate change, social justice, and the supply chain issues (Black, 2013). Or, conservation agriculture may support farmers and their local stakeholders to target multiple biophysical and socio-economic goals (Lalani *et al.*, 2021). At a planetary scale, systems mapping approaches can support identifying practices that simultaneously pursue goals of global food security and climate mitigation and adaptation goals (Vermeulen *et al.*, 2012; WEF, 2021). Hence, these systems mapping processes help societal actors to visualize and choose between multiple pathways towards agri-food systems change (Horton *et al.*, 2016; Dentoni *et al.,* 2017). Furthermore, targeting multiple goals provides avenues for a visually tangible discussion on how to achieve multiple and plausibly conflicting objectives, such as the pursuit of economic versus environmental benefits. Altogether, these systems mapping processes support changes in "the system by improving the relationships among its parts, not optimizing each part separately" (Stroh, 2015: 28).

5.2. Generating ripple effects

The second implication of the described systems mapping processes is that participants, when underpinned with sufficient understanding of systems, will become more purposive in how they generate ripple effects. As systems are interdependent, path-dependent, and self-organizing, our actions and interactions trigger, support or shape chains of causally connected events in our environment; of course, not only in desirable ways. For example, human-caused climate change "has dramatically altered the hydrologic cycle of the western United States, which in turn has influenced the economics of irrigation for farmers and has consequences in farm labour dynamics, hydroelectricy energy supply and freshwater ecology" (Levy *et al.*, 2018: 413). The described systems mapping processes make societal actors more aware of these ripple effects and how they can together enact systems change in desirable directions. In particular, the purposive generation of ripple effects via systems mapping can support the scaling of transformative actions (Kerton and Sinclair, 2010; Tobias *et al.,* 2013) also to novel contexts, provided that participants with deep understanding of those contexts are engaged in the mapping processes. For example, public agencies and local incubators could strategize how to support entrepreneurial behaviors and identities in rural post-conflict areas, such as Rwanda in the 2000s, in ways that reduces poverty and attenuates social tensions (Tobias *et al.,* 2013). In doing so, farmer field schools could play an important role to trigger ripple effects in food and agriculture through processes of learning (Duveskog *et al.,* 2011). Or, community-supported agriculture initiatives could involve municipalities to expand their food production and civic outreach in ways that, in turn, engage their neighbors in processes of food lifestyle change (Kerton and Sinclair, 2010). This purposive way of strategizing how to trigger or support ripple effects through systems mapping would be important for several ongoing institutional attempts of supporting agri-food systems transformation (EU Environment Agency, 2022; Environmental Initiative, 2022).

5.3. Mitigating unintended consequences

As a third implication, we argue that systems mapping supports anticipating and reducing the risk of negative consequences of their envisioned actions. From the extant literature, we know that actions meant to address socio-ecological problems in food and agriculture may often have unpredicted and undesirable side effects (Stroh, 2015), as often "today's problems come from yesterday's solutions" (Kofman and Senge, 1993: 5). For example, fertilizer subsidies – while meant to increase food productivity and reduce food insecurity – reduce farmers' incentives for crop diversification, hence reducing their soil fertility over time (Theriault and Smale, 2021). Or, climate change mitigation policies related to land-use change emissions can have negative side effects on local water demands (Giuliani *et al.,* 2022). What we know less is how we can purposively and systematically consider them and mitigate their undesirable effects (Martí, 2018; Dentoni *et al.,* 2021), especially in the domain of food and agriculture. Systems mapping processes that take sufficiently into account these non-linear, complex and multi-level dynamics (such as the one hereby described in section 4) addresses this limitation. By collectively discussing the possible side effects, participants of systems mapping workshops can identify the possible unintended consequences and the actions to undertake in case that these occur. This collective discussion prepares societal actors to reflect upon plausible unintended effects of their actions and be accountable to each other in mitigating these effects, when negative. For example, the European Commission and its stakeholders could use systems mapping to make sense and respond to negative claims on their Farm to Fork strategy by some of their detractors (European Scientist, 2021; Farm Europe, 2021). These include, for example, the claimed negative side effects of investing on organic and regenerative agriculture policies and regulating biotechnology on farms' food production and revenues, ultimately with consequences on European food security. Considering these claims on negative consequences of the Farm to Fork strategies may help European policy-makers and their stakeholders to develop actions that mitigate these risks, and narratives that counter these claims.

5.4. Tackling systemic constraints

As a fourth implication, systems mapping approaches (when grounded with sufficiently deep understanding of systems) help societal actors to identify and address systemic constraints that prevent lock-ins to be addressed (see details in section 4.2). Systemic constraints risk to turn interventions in a system into 'fixes that backfire' (see Stroh, 2015: 54). These fixes are relatively quick, short-term, apparently clever actions (sometimes not-so-cleverly labeled as 'low-hanging fruit' interventions) that do not produce desirable long-term impacts because their causal mechanisms have not been addressed in sufficient depth. For example, direct subsidies of local agriculture (in terms of farm size or production) may have short-term desirable effects on food security and rural development, yet may not tackle systemic constraints of agricultural adaptation to climate change, for example in terms of water and energy efficiency (WRI, 2021). Through systems mapping, instead, societal actors can strategize how to combine 'quick fixes' with more fundamental work that addresses systemic constraints. For example, the Consultative Group for International Agricultural Research (CGIAR) noted that farmers' adoption of climate mitigation and adaptation practice also grounded into a limited organizational capacity of researchers to work across disciplinary and sectoral silos to support agri-food systems transformation (ISDC, 2021). On the basis of this realization, the organization reformed its internal structure and its relationships with public agencies and private foundations to foster inter-and trans-disciplinary research and innovation which, ultimately, could create more favorable systemic conditions for farmers' adoption. Hence, in engaging in these deeper change processes, we recommend societal actors like the CGIAR to make use of sufficiently deep systems mapping approaches.

5.5. Collaborating with unconventional partners

As fifth and final implication, when they sufficiently consider the features of systems, systems mapping approaches help participants to set up very much needed collaboration with unconventional partners. We already know from the agri-food systems literature that building weak ties (that is, relationships with actors across circles that are other otherwise very disconnected) may help societal actors to support sustainable transformations (Nelson *et al.,* 2014; Dentoni *et al.,* 2020). For example, building structural relationships between life scientists and social scientists, or between higher education institutes, policy-makers and communities, or between vocational trainings, tech companies and farmers may foster agri-food systems adaptation to and mitigation of socio-ecological challenges (Dentoni *et al.,* 2020; Rosenstock *et al.,* 2020). Yet, current food and agricultural studies do not yet inform how to prioritize and set up these much-needed forms of unconventional collaboration. Appropriate systems mapping processes, such as an iterative combination of causal loop diagrams and value network maps, contribute understanding how to do so. Through causal loop diagrams, participants can visualize how to prioritize unusual collaborations to act upon leverage points in the system. For example, having identified farmer business trainings as a critical lever to empower rural communities in linking them to legume and maize markets, the Malawian Agricultural Commodity Exchange (ACE) developed rural incubators with local farmer field schools and higher education institutions (Dentoni *et al.,* 2020). Complementarily, through value network maps describing current and potential resource flows among actors in a system, participants can visualize how to distribute appropriate incentives for unconventional partnerships to work in practice. For example, the Malawian Agricultural Commodity Exchange engaged farmer field schools and training organizations through international and national funding, while developed incentives for farmers and agricultural commodity storage operators to collaborate through warehouse receipt systems financed by national banks (Dentoni *et al.,* 2020). For the Malawian agri-food context and beyond, these partnerships were novel and contributed to change the system towards more interconnected, resilient and food secure rural areas. Finally, as systems mapping involves collective creation and visualization of resources and incentives potentially available among actors in a system, it encourages participants to the same session to brainstorm and negotiate concrete possibilities of collaboration, partnership, and collective action in a multilateral setting. Hence, by inviting mutually disconnected actors, but accessing potentially complementary resources, facilitators of systems mapping workshops may purposively steer the opportunities of building these unconventional partnerships.

6. CONCLUSION

The scale, persistence and aggravating nature of the socio-ecological problems that we face in and around the food and agricultural sector force us to undertake novel, bold, and interdisciplinary endeavors to address them. Widely applied in other social and ecological contexts, the use of systems thinking processes has rapidly expanded also in food and agriculture in the last decade, yet still lacking the depth sufficient to address the complexity of the problems at hand. As a result, narratives around 'food systems approaches', 'systems change' and 'food systems transformation' are dangerously becoming meaningless buzzwords. These worrying trends and scientific limitations urgently call scholars to propose systems mapping processes for societal actors - including us as researchers and educators - to better comprehend and address complex social and ecological issues in collective settings, while grounding them approaches in sufficiently deep understandings of what systems really mean.

Based on a review of the agri-food literature applying systems thinking in contrast with the key features of systems, we first argued that the food and agriculture literature has so far struggled to reach sufficient depth to support societal actors and researchers in addressing the complex socio-ecological problems at hand. Second, to overcome this limitation, we proposed a systems mapping processes that – through the use of causal loop diagrams and value network maps – iteratively combines the collective visualization of systems of issues and systems of actors in collective settings. Finally, we demonstrated how combining the mapping of systems of issues and systems of actors provides a powerful way to understand, in practice, how complex problems and complex systems are two sides of the same coin. When undertaken with adequate participatory processes (Király *et al.,* 2016; Wilkinson *et al.,* 2021), these systems mapping processes help develop individual competencies and collective understandings for participants to purposively target multiple goals, generate ripple effects, mitigate unintended consequences, tackle systemic constraints and build collaborations with unconventional partners. Hence, by making sense of systems and envisioning how to change them, these systems mapping processes can equip participants with different roles and viewpoints in societal to become better equipped to address socio-ecological problems confronting them.

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Vulnerability and resilience to food and nutrition insecurity: A review of the literature towards a unified framework

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Abstract. Current approaches to measuring food and nutrition security (FNS) mainly consider past access to food, while assessing vulnerability and resilience to food insecurity requires a dynamic setting and sound predictive models, conditional to the entire set of food-related multiple-scale shocks and stresses as well as households' characteristics. The aim of this work is twofold: i) to review the state of the relevant literature on the conceptualization and the empirical measurement of vulnerability and resilience to food insecurity; ii) to frame the main coordinates of a possible unifying framework aiming at improving ex-ante targeting of policy interventions and resilience-enhancing programs. Our argument is that clarifying the relationships existing between vulnerability and resilience provides a better understanding and a more comprehensive picture of food insecurity that includes higher-order conditional moments and non-linearities. Furthermore, adopting the proposed unified framework, one can derive FNS measures that are: scalable and aggregable into higher-level dimensions (scale axiom); inherently dynamic (time axiom); conditioned to various factors (access axiom); applicable to various measures of food and nutrition as dependent variables (outcomes axiom). Unfortunately, the proposed unified framework shows some limitations. First, estimating conditional moments is highly data-demanding, requiring high-quality and high-frequency micro-level panel data for all the relevant FNS dimensions, not mentioning the difficulty of measuring risks/shocks and their associated probabilities using short panel data. Hence, there is a general issue of applicability of the proposed approach to typically data-scarce environments such as developing contexts. Second, there is an inherent tradeoff between the proposed approach in-sample precision and out-of-sample predictive performance. This is key to implement effective early warning systems and foster resilience-building programs.

Keywords: vulnerability, resilience, food security, nutrition.
JEL Codes: I32, O12, Q12.

1. INTRODUCTION

In an ideal world, agrifood systems would be resilient, inclusive and sustainable, producing sufficient, safe and nutritious food for all, and generating livelihoods that guarantee people's economic access to that food (FAO *et*

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al., 2021). In stark reality, agrifood systems fail to keep about 10 percent of the world's population free from hunger (FAO *et al.*, 2022) and agrifood supply chains and livelihoods are increasingly exposed to multiple stressors: droughts, floods, armed conflict, food price hikes, and long-term stresses, including climate change and environmental degradation (FAO, 2021).

This challenges the received wisdom on food and nutrition security (FNS) measurement, analysis and policymaking. In fact, current approaches to measuring FNS mainly consider past access to food, failing to provide policymakers with forward-looking information and a good understanding of the wider risks that households face (Capaldo *et al.*, 2010). Conversely, assessing vulnerability and resilience to food insecurity requires a dynamic setting and sound predictive models, conditional to the entire set of food-related multiple-scale shocks and stresses as well as households' characteristics (Upton *et al.*, 2016; Ibok *et al.*, 2019).

The aim of this work is twofold: i) to review the state of the relevant literature on the conceptualization and the empirical measurement of vulnerability and resilience to food insecurity; ii) to frame the main coordinates of a possible unifying framework between vulnerability and resilience – and the related concept of poverty trap – aiming at improving ex-ante targeting of policy interventions and resilience-enhancing programs.

Our argument is that clarifying the relationships existing between vulnerability, poverty traps and resilience allows getting a better understanding and more comprehensive picture of FNS, that is able to satisfy all the relevant axioms to FNS measurement as highlighted by Upton *et al.* (2016). Specifically, one can derive FNS measures that are: scalable and aggregable into higher-level dimensions (scale axiom); inherently dynamic (time axiom); conditioned to various factors (access axiom); applicable to various measures of "active and healthy life" as dependent variables (outcomes axiom). Unfortunately, as reported more in detail in this review, the proposed unified framework requires some pre-conditions: first, it is computationally intensive, thus it requires high-quality and high-frequency micro-level panel data for all the relevant dimensions to FNS, not to mention the difficulty of measuring risks/shocks (and their self-reported proxies) and their associated probabilities using short panel data. Hence, there is a general issue of how to combine this unifying measurement approach with the typical data-scarce environments that are common in developing contexts. Second, although there are specific situations where these measures could be effectively implemented, there is an inherent tradeoff between their in-sample precision and out-of-sample predictive performance.[1] This is key if the aim is implementing effective early warning systems and resilience-building programs in the most fragile agri-food systems. In this respect a promising route could be improving the interoperability of traditional survey data with non-conventional data sources (big data, crowdsourced data, citizen-generated information, etc.), although many technical and institutional challenges remain (Carletto, 2021).

The rest of the work is organized as follows: Sections 2 and 3 review the relevant literature on vulnerability and resilience, respectively, by addressing conceptualization, measurement issues and empirical evidence; Section 4 depicts the state of the art of the analysis of both vulnerability and resilience as applied to food insecurity; Section 5 describes a possible unifying framework; Section 6 concludes and provides some key recommendations for future research.

2. Vulnerability

2.1. The emergence of vulnerability concept

The concept of vulnerability to poverty aims at answering a simple but crucial question: what is the likelihood that an individual or a household will be poor in the next future? Unfortunately, providing an answer to this question is not an easy task. First, we need to agree on a common social norm in terms of welfare (e.g., consumption), and on a common benchmark (e.g., the poverty line). Second, although vulnerability is strictly linked to poverty, the two concepts are different. Current poverty is an ex-post status referring to the static situation in which the individual lives at the very same moment it is observed and measured, whereas vulnerability means predicting future poverty (Chaudhuri *et al.*, 2002). Indeed, the concept of vulnerability, which is an inherently forward-looking construct of the expected outcomes (Alwang *et al.*, 2001), is neither directly observable nor linked to the actual manifestation of shocks (Imai *et al.*, 2011; Magrini *et al.*, 2018). As a result, poor households ex-post are not necessarily so ex-ante and correlates of vulnerability may differ from those of poverty. This distinction plays a crucial role when designing policies: targeting only the currently poor could exclude a significant group of individuals that risk experiencing a welfare loss, i.e., the vulnerable groups. Along with pro-poor policies (policies directly targeting poor people), we also need to carry out pre-

[1] This is the traditional issue of "overfitting" in data driven approaches. In fact, these approaches tend to learn too well the training data to the extent that it negatively impacts the out-of-sample predictive performance (Hastie *et al.*, 2009).

ventative strategies directly targeting the vulnerable ones (Montalbano, 2011). Third, vulnerability is a complex subject not identified by a single, easily measurable construct. All individuals, households, communities and even nations face multiple risks, natural or man-made, idiosyncratic and covariate, from different sources. Hence, as emphasized by Hoddinott and Quisumbing (2003), there is a wide consensus on what vulnerability means in general terms but, when we attempt to analyze it in detail, the concept tends to blur and become subsumed in the haze of the multifarious situations of vulnerability, giving only context-specific interpretations. As a result, a proliferation of methodologies, terminology and approaches to vulnerability analysis have been applied to a broad range of topics (e.g., food security, natural disasters, conflict prevention, economic fragility, etc.). Scholars, research centers, multilateral and bilateral organizations and agencies have developed their own definitions and methods to analyze vulnerability. It is notable that not all these definitions include the same key elements and they also use slightly different terminology. Hence, practitioners from different disciplines use different meanings and concepts of vulnerability (Alwang *et al*., 2001).

2.2. Vulnerability approaches

Different approaches to vulnerability also lead to different methods of estimation. Along with a set of more holistic approaches, such as the traditional sustainable livelihood approach (Chambers and Conway, 1992), that looks at the capacity of communities to sustainably maintain their own livelihoods,[2] there are analyses of vulnerability that typically express welfare in terms of consumption and focus on consumption variability as a proxy for economic instability. Among the latter, the earliest efforts attempt to measure vulnerability simply as the negative impact on household's consumption from exposure to a set of observed risks (the so-called *Vulnerability Exposure to Risk*, see Glewwe and Hall, 1998; Dercon and Krishnan, 2000). Later efforts measure vulnerability as loss in expected welfare in an uncertain environment (Chaudhuri, 2001 and 2003; Ligon and Schechter, 2003; Calvo and Dercon, 2013). Various reviews of the literature (Hoddinott and Quisumbing, 2003; Povel, 2015; Gallardo, 2018) consistently grouped these most recent monetary methods into the following broad categories: *Vulnerability to Expected Poverty* (Chaudhuri, 2001 and 2003; Chaudhuri *et al*., 2002; Pritchett *et al*., 2000); *Vulnerability as low Expected Utility* (Ligon and Schechter, 2003 and 2004); *Vulnerability as the Threat of Future Poverty* (Calvo and Dercon, 2003 and 2013). Each of these vulnerability approaches presents its own strengths and weaknesses. Here below, we present the main characteristics of each of them.

[2] The sustainable livelihood approach looks at vulnerability as a general concept capturing two main aspects: (i) insecurity in the wellbeing of individuals, households, and communities because of changes in their external environment, and (ii) lack of ability and means to cope because of an internal defenselessness (Serrat, 2017).

Vulnerability as Expected Poverty

The Vulnerability as Expected Poverty (VEP) approach is the most controversial but commonly applied method (Christiaensen and Boisvert, 2000; Pritchett *et al*., 2000; Chaudhuri, 2001 and 2003; Chaudhuri *et al*., 2002; Christiaensen and Subbarao, 2005). It assesses vulnerability simply as the expected value of the standard Foster-Greer-Thorbecke (FGT) class of decomposable poverty measures (Foster *et al*., 1984) as follows:

$$VEP_{h,t} = F(z)\int_0^z \left(max\left\{0, \frac{z-c_{h,t+1}}{z}\right\}\right)^{\alpha} \frac{f(c_{h,t+1})}{F(z)} dc_{h,t+1} \quad (1)$$

where $c_{h,t+1}$ is household's consumption in the near future; z is the standard poverty line; $\alpha \geq 0$ is the "poverty aversion" parameter; $F(\cdot)$ and $f(\cdot)$ indicate, respectively, the cumulative distribution and the density function. Eq. 1 measures the probability of households falling below the poverty line, multiplied by a conditional probability-weighted function of the shortfall below it (Christiaensen and Boisvert, 2000). The parameter α in Eq. 1 sets the degree of sensitivity of the vulnerability measure to the distance from the poverty line.[3] When $\alpha=0$, VEP measure reduces to the probability that the household will experience poverty, i.e $V=F(z)$.[4] The distribution f is taken as given and reflects both the households' exposure to shocks (idiosyncratic or covariant) and its ability to cope with them.

Empirically, on the assumption that consumption is log-normally distributed, setting the consumption poverty threshold, z, and a threshold probability value above

[3] This is the key parameter in FGT class of poverty measures (Foster *et al*., 1984). The case $\alpha=0$ yields a distribution of individual poverty levels in which each poor person counts 1; the ratio of the total poor count to the entire population is simply the poverty headcount ratio. The case $\alpha=1$ uses the normalized gap as a poor person's poverty level, thereby differentiating among the poor according to their relative distance from the poverty line. The case $\alpha=2$ squares the normalized gap and thus weights the gaps by the gaps. As α tends to infinity, the condition of the poorest poor is all that matters.

[4] Most works (Christiaensen and Boisvert, 2000; Pritchett *et al*., 2000; Chaudhuri and Datt, 2001; Chaudhuri *et al*., 2002) rely on this choice indeed, but there are also some VEP applications which look at the depth of the poverty ($\alpha=1$) and at the spread of its distribution ($\alpha=2$).

an accepted norm at which a household is considered vulnerable (e.g., Pr > 0.5), it is possible to estimate vulnerability to expected poverty as the probability at time t of a household with characteristics X_h to fall below the poverty line in the near future using the estimated expected mean ($\widehat{c_h}$) and variance ($\widehat{\sigma_h^2}$) of its log consumption, as follows:

$$VEP_{h,t}=Pr(log\ c_{h,t}<log\ z \mid X_{h,t})= \Phi\left(\frac{log\ z - log\ \widehat{c_{h,t}}}{\sqrt{\widehat{\sigma_{h,t}^2}}}\right) \quad (2)$$

where Φ is the cumulative density of the standard normal distribution.

The main assumption of the VEP approach is that environment is stationary and the variance of the residuals in cross-sectional consumption regressions (i.e. the unexplained part of household consumption) is not simply a measurement error and is not equal across households. It rather captures the impact of both idiosyncratic and covariate shocks on consumption, which can be explained by a set of observable household characteristics. The main advantage of the VEP method follows directly from this assumption: vulnerability can be assessed using only a single round of cross-sectional data. This is also the source of its main limitation: cross-sectional variability proxies inter-temporal variance in consumption (hence, it does not consider the impact of household-invariant but time-variant shocks). Furthermore, the distribution of shocks to consumption is independent normal, which contrasts with the empirical evidence on the relatively higher risk aversion of the poor. Finally, the standard version of the approach is not able to differentiate between the impact of idiosyncratic shocks and the impact of covariate shocks.

Acknowledging the latter caveat, Sarris and Karfakis (2006) and Gunther and Harttgen (2009) present different methods to disentangle VEP measures assessing separately the impact of covariate shocks at the community level and the idiosyncratic ones at the household level. More specifically, Gunther and Harttgen (2009) acknowledge the hierarchical structure of community and household variables by applying a multilevel analysis. Hence, they decompose the unexplained variance in households' consumption into a lower-level (i.e., household) and a higher-level (i.e., community) component. On top of that, the VEP method essentially lacks a solid theoretical background and displays a somewhat perverse feature relating to the measure of the welfare consequences of risks: it implies a reduction of vulnerability by increasing the variability of consumption around the poverty line, which is in sharp contrast to the poor being risk averse (Hoddinott and Quisumbing, 2003). [5]

Vulnerability as Low Expected Utility

The Vulnerability as Low Expected Utility (VEU) model tries to counteract the weak theoretical background of the VEP class of measures by proposing a risk-sensitive measure of vulnerability based on expected utility (Ligon and Schechter, 2003 and 2004). According to this approach, the vulnerability of household h is measured as the difference between the utility derived from some level of certainty-equivalent consumption, z_{ce}, above which the household would not be considered vulnerable (i.e., something analogous to a poverty line in the standard ex-post poverty analysis), and the expected utility of future consumption as follows:

$$VEU_h=U_h(z_{ce})-EU_h(c_{h,t}) \quad (3)$$

where U_h is a weakly concave, strictly increasing function. In addition, the VEU method enables the decomposition of vulnerability into two distinct components: vulnerability to poverty, that is, low expected consumption, and vulnerability to risk, that is, high volatility of consumption, as follows:

$$VEU_h=[U_h(z_{ce})-U_h(Ec_{h,t})]+[U_h(Ec_{h,t})-EU_h(c_{h,t})] \quad (4)$$

where the first bracketed term (i.e. the difference in utility at z_{ce} compared to the utility of households' expected consumption) is a measure of vulnerability to poverty and involves no random variables, while the second term, according to the ordinal measures of risk proposed by Rothschild and Stiglitz (1970), measures vulnerability to risk.[6] Moreover, the risk component can be further

[5] To clarify this point, Hoddinott and Quisumbing (2003) provide the following example. Consider two scenarios. In the first scenario, a risk-averse household is certain that its expected consumption in period t+1 will be just below the poverty line. In this case, its computed VEP is accurately equal to 1. In the second scenario, the mean expected consumption remains unchanged, but the household faces a small amount of variability in consumption such that there is a 50% chance of having consumption just above or just below the poverty line. As poor households are risk averse, this second scenario implies a decrease in welfare (as the household would prefer a certain level of consumption over a fluctuating expected consumption). However, the VEP measure – which registers the fluctuation as a 50% chance of escaping poverty – will decrease from 1 to 0.5. This leads to a perverse policy implication, as using VEP a policymaker aiming to reduce vulnerability should actually introduce new sources of risk.

[6] This is the natural counterpart, measured in utility units, of the risk premium the household would be willing to pay in order to eliminate the risk. It can be measured, starting from a (weakly) concave utility

decomposed into covariate and idiosyncratic components. Let $EU_h(x_{h,t})$ be the expected value of consumption conditional on a vector of covariant variables $x_{h,t}$, then we can rewrite the VEU measure as follows:

$$VEU_h=[U_h(z_{ce})-U_h(Ec_{h,t})]+[U_h(Ec_{h,t})-EU_h(c_{h,t}|x_{h,t})]+[EU_h(c_{h,t}|x_{h,t})-EU_h(c_{h,t})] \quad (5)$$

where the first bracketed component is again vulnerability to poverty, but the second and third components break down vulnerability to risk into two sub-components: vulnerability to covariate risks and vulnerability to idiosyncratic risks. To avoid confusion between the measurement error and idiosyncratic risk, Ligon and Schechter (2003) further decompose their measure of idiosyncratic risk into the risk that can be attributed to a set of distinct, observed, time-varying characteristics. The advantage of this measure is that it can be conveniently adapted to assess vulnerability related to a set of possible sources of risks. For instance, Ligon (2006) and Magrini *et al.* (2018) propose similar measures of vulnerability able to decompose country-level and "meso" risks, respectively, from aggregate ones, by further decomposing the risk component of the VEU measure as follows:

$$\begin{aligned}(VEU_h=&[U_h(z_{ce})-U_h(Ec_{h,t})] + && \text{[poverty]}\\ &[U_h(Ec_{h,t})-EU_h(c_{h,t}|\mu_k)] + && \text{[meso risk]}\\ &[EU_h(c_{h,t})|\mu_k)-EU_h(c_{h,t}|\mu_k,\mu_t)] + && \text{[aggregate risk]} \quad (6)\\ &[EU_h(c_{h,t}|\mu_k,\mu_t)-EU_h(c_{h,t}|\mu_k,\mu_t,x_{h,})] + && \text{[idiosyncratic risk]}\\ &[EU_h(c_{h,t}|\mu_k,\mu_t,x_{h,t})-EU_h(c_{h,t})] && \text{[unexplained risk/ measurement error]}\end{aligned}$$

where μ_k represents a risk term which varies across k clusters of units characterized by heterogeneity in their exposure to global risks, whereas μ_t is an aggregate risk term, common to all units, which may vary over dates and (aggregate) states of nature.

The VEU measure of vulnerability raises three main and interrelated concerns too: first, the obvious circumstance that the choice of a specific form of the utility function directly affects the magnitude of the phenomenon; second, the difficulty to transform VEU measures of vulnerability, expressed in utility units, into actual economic policy targets (Hoddinott and Quisumbing, 2003); third, the fact that it does not satisfy the so-called "focus axiom" ensuring that the vulnerability measure should be exclusively sensitive to negative future outcomes whereas positive future outcomes should be not reflected in the measure (Calvo and Dercon, 2013).[7]

function, as the difference between the utility of consuming the expected consumption with certainty and the expected utility from consuming c_h.

[7] Calvo and Dercon (2003) clarify this providing the following example. Consider a poor that buys each week a state lottery ticket. She spends a very small sum of money, but 'you never know', and there is a 0.001 percent chance of winning the top prize of $10,000. If the focus axiom was not applied, it would be sufficient to increase the top prize to make her less vulnerable. Again, a kind of perverse policy implication can be derived by applying this vulnerability measure.

Vulnerability as the Threat of Poverty

The Vulnerability as the Threat of Poverty (VTP) class of vulnerability measures tries to overcome some of the weaknesses of both VEP and VEU methods (Calvo and Dercon, 2003; Calvo 2008; Calvo and Dercon, 2013; Povel, 2015). Starting from the assumption that people suffer and are wary of the future if their knowledge of what it holds is uncertain, VTP measures associate vulnerability to the extent that poverty cannot be safely ruled out as any of the possible future scenarios (Calvo, 2008). Specifically, the VTP approach measures vulnerability as a probability-weighted average of future indices of deprivation in different states of the world as follows (Calvo and Dercon, 2013):[8]

$$VTP_{h,t}=1-E[x^{\alpha}{}_{h,t}] \quad (7)$$

where $x_{h,t}$ is an index of deprivation, i.e., represents the rate of coverage of basic needs, which is derived for each state of the world as $x_{h,t}=\frac{\tilde{y}_{h,t}}{z}$, where $\tilde{y}_{h,t}(y_{h,t})$; z) is censored at z; $y_{h,t}$ is the consumption level (after all consumption smoothing efforts have been deployed); z is the standard poverty line; and $0<\alpha<1$ represents risk sensitivity[9] as when α increases to 1, the household approaches risk-neutrality.

This measurement combines households' exposure to risks with deprivation and shortfalls in welfare indicators. In this respect, the VTP measure represents an improvement of both VEP and VEU. VTP is risk-sensitive and satisfies the so-called focus axiom, according to which the burden of future poverty will not be compensated by possible future positive outcomes. This means that uncertainty/risk not related to poverty in any state of the world does not enter this measure of vulnerability. Furthermore, VTP is not affected by outcome changes above the poverty line. However, two main caveats apply to the use of the VTP measure as well. Firstly, for those facing no uncertainty with known $x_i=x^*<1$ for all i, then $VTP>0$. In other words, being poor is the dominant threat in terms of vulnerability. However, there is no agreement on this in the literature that traditionally

[8] A multidimensional extension of VTP has been proposed by Calvo (2008) using data from Peru (1998–2002).

[9] The parameter α is not only an index of risk aversion but it is also comparable to the from the Foster-Greer-Thorbecke measure of poverty in so far it measures the severity of possible future poverty.

distinguishes the determinants of poverty from those of vulnerability. Secondly, the empirical strategy of VTP implies the use of lengthy panel data to retrieve predictions of the rate of coverage of basic needs and the distribution of random idiosyncratic shocks looming for households in the future in various states of the world (Calvo, 2008). This is not only subject to misspecifications and measurement errors but assumes a time-invariant discrete uniform distribution of shocks, which is indeed an assumption as strong as proxying inter-temporal variance with cross-sectional variability, as made by the VEP method.[10] Although VTP surely constitutes a generous effort of building an axiomatic approach to vulnerability,[11] it lacks robust empirical analyses capable of providing a clear added value to its common alternative measures.

Recent attempts to adapt vulnerability to the field of food insecurity have been implemented by Bogale (2012), Sileshi *et al.* (2019) and Ibok *et al.* (2019). In this framework, we can distinguish two main strands of vulnerability analysis: (i) tentative adaptations to food insecurity of households' probability to fall below the food poverty line, mainly in cross-sectional settings (Capaldo *et al.*, 2010; Sileshi *et al.*, 2019; Gattone at al., 2022); (ii) the elaboration of multidimensional indices to measure household's food insecurity and contextual vulnerability as a latent variable (Ibok *et al.*, 2019). Although multidimensional indices cannot capture the forward-looking aspect of vulnerability, they can be used to develop vulnerability maps of FNS, i.e., hotspots reflecting locations with high exposure and sensitivity but low adaptive capacity (de Sherbinin, 2014).

To measure contextual vulnerability, Ibok *et al.*, (2019) compute a vulnerability to food insecurity index (VFII) that includes three main components, that are the exposure index (E_h), the sensitivity index (S_h) and the adaptive capacity index (AC_h), as follows:

$$VFII_h = \sum AC_h - (\sum E_h + \sum S_h). \tag{8}$$

Exposure refers to food-related shocks that affect the household access to safe and nutritious food and is widely defined as the degree to which a system faces risk, shock or hazard. The sensitivity component measures the previous or cumulative experience of food insecurity, such as stunting, child mortality, and hunger within the household. Adaptive capacity is the ability of households to successfully adjust to the effect of food-related shocks through coping mechanisms (Engle, 2011).

2.3. Empirical evidence

By using a set of Monte Carlo experiments, Ligon and Schechter (2004) explore the performance of the above vulnerability measures and estimators. They find that estimating vulnerability from cross-sectional data (such as in the case of VEP) leads to estimates which are even inferior to simple static poverty measures, essentially because they lack control for risk sensitivity. Conversely, panel data with a longitudinal dimension as short as two years for a few thousand units (roughly the size of the typical World Bank's Living Standard Measurement Survey datasets) allow estimating vulnerability almost close to its limiting values. However, this holds for short stationary panel. Elbers and Gunning (2003) offer an elegant solution to the non-stationarity issue in long panels, using a structural dynamic model to derive simulation-based estimates of vulnerability that incorporate both risks and predictable variation in consumption over time. Thanks to their dynamic exercise they demonstrate that much of the effect of risk on the mean of the ergodic distribution of consumption reflects the ex-ante effect, that is a household can be chronically poor because its response to risk lowers average consumption permanently. This implies that mean consumption is not independent of risk as implicitly assumed by the standard vulnerability measures. As a result, by ignoring any behavioral response to risk (e.g., consumption smoothing) all the above vulnerability measures underestimate the overall effect of risk in measuring vulnerability. Elbers and Gunning (2003) argue that, using simple regression-based methods, one could accurately identify vulnerable households provided that asset data are included as regressors to proxy such ex-ante behavioral responses to risk.[12]

A key feature is thus the risk sensitivity of the applied vulnerability measures. Ligon and Schechter (2003) and Magrini *et al.* (2018) looking at differ-

[10] Think, for instance, at the unprecedented change in the frequency and severity of shocks brought about by climate change.

[11] Apart from the aforementioned "focus axiom", Calvo and Dercon (2007) propose an additional set of axioms to be satisfied by their vulnerability measure: "symmetry over states" (i.e., the only relevant difference between two states of the world *i* and *j* should be the difference in their outcomes and probabilities; "continuity and differentiability" of the vulnerability function; "scale invariance" (i.e., vulnerability measure should not depend on the unit of the measure of outcomes); "normalization" to impose boundaries for reasons of comparability; "probability-dependent effect" of outcomes (i.e., vulnerability should be sensitive to the likelihood of that particular state of the world); "probability transfer" (i.e., if y_j is greater than or at least equal to y_i, then vulnerability cannot increase as a result of a probability transfer from state *j* to state *i*); "risk sensitivity" (i.e., greater risk should increase vulnerability); "constant relative risk sensitivity" (i.e., risk sensitivity remains constant if all state specific outcomes increase proportionally).

[12] This is important empirical evidence supporting section 5 arguments.

ent samples of Bulgarian and Vietnamese households, respectively, consistently demonstrate that the average welfare under risk is lower than it would be in a certainty-equivalent scenario and that this was not necessarily linked to the actual manifestation of shocks. Klasen and Waibel (2013) and Povel (2015) reach a similar conclusion, showing that rural households in Vietnam (and to a lesser extent in Thailand thanks to higher opportunities for diversification) were vulnerable because more exposed to downside risks amid local reforms.

Capaldo *et al.* (2010) were the first to estimate vulnerability to food insecurity. They computed it as the normal probability that the individual minimum dietary energy requirement under light physical activity is lower than the expected individual dietary energy consumption (measured in kilocalories). They apply the standard VEP measure (Eq. 1) by simply substituting a measure of household's expected dietary energy consumption for consumption expenditure. In a similar effort, Gattone *et al.* (2022) use as outcome variable both raw and standardized scores of the Food Insecurity Experience Scale (FIES).[13] These authors also exploit machine learning algorithms to select the most predictive combinations of household characteristics thus getting pure stochastic residuals.

Thanks to the availability of panel data, Letta *et al.* (2022) adapt VTP to food insecurity following the extension proposed by Povel (2015). Using information about the occurrence of the shocks and estimating the related loss of income, Letta *et al.* (2022) predict the deprivation indexes associated to all the different states of the world that are given by the different combinations of shocks the household might face, by applying the following ex-ante measure of household vulnerability:

$$VTP_h=\sum_{j=1}^{N_i}\left(p_{hj} \times x_{hj}^{\alpha}\right) \tag{9}$$

where $N_i=\sum_{k=0}^{K_i}\frac{K_i!}{(K_i-k)!k!}$ represents the number of possible states of the world; p_{hj} represents the probability of the state of the world j to occur (it ranges between zero and one); x_{hj}^{α} denotes the deprivation index, namely the loss of income in the state of the world j, measured as $x_{hj}=\sum_{q=1}^{Q_{hj}}\frac{s_{hjq}}{y_h}$, where s_{hjq} represents the severity of the shock q and y_h is the household income. To distinguish between households vulnerable to income losses but not experiencing food insecurity, Letta *et al.* (2022) also use FIES data.

[13] These scores have been implemented under FAO's project Voices of the Hungry and represent a subjective survey-based experiential measure of FNS aimed at overcoming the lack of multidimensionality of the traditional measures of food insecurity vulnerability, like food consumption or per capita food intake (Cafiero *et al.*, 2018).

3. RESILIENCE

3.1. The emergence of resilience concept

The concept of resilience has been used in fields as different as engineering, psychology, ecology and epidemiology since long ago. Mechanical and civil engineers were probably the first to use this concept back in nineteenth century as the capacity of different materials to absorb loads (McAslan, 2010). Psychologists began referring to resilience in the 1970s (Rutter, 2012) as the overcoming of a stress or adversity, or a relatively good outcome despite risk experiences. In the same years, ecologists developed different notions of resilience such as the amount of disturbance an ecosystem can absorb before shifting into an alternative state (Holling, 1973) or the speed of return to a pre-existing equilibrium following a perturbation or shock (Pimm, 1984). More recently, the literature on socio-ecological systems (Gunderson *et al.*, 1997; Levin *et al.*, 1998; Reyers *et al.*, 2018) emphasized resilience as "the ability of people, communities, societies, and cultures to live and develop with change, with ever-changing environments" (Folke, 2016: 3). In this literature, the concept of resilience has been used to inform analysis of change in economic and ecological systems, suggesting the advantages of analyzing change in the system as a Markov process, with the transition probabilities between states offering a natural measure of the resilience of the system in such states (Perrings, 1998 and 2006).[14]

The emergence of the resilience concept in economics and FNS analysis is relatively recent and basically related to the emphasis put by humanitarian and development agencies on the need to integrate humanitarian (i.e., short-run, emergency) interventions and development (i.e., long-run) intervention. The Hyogo Framework for Action, that represents the most important result of the World Conference on Disaster Reduction (UNISDR, 2005), and more recently the UN World Humanitarian Summit (UN, 2016), identified the so-called human-development-peace nexus as a key principle informing the operations of multilateral as well as bilateral cooperation agencies[15]. As emphasized by the multi-agency

[14] At the best of our knowledge, Perrings (1998) was the first modelling the economy-environment systems dynamics as a Markov process and defining resilience as transition probabilities between different future states. This intuition is also crucial for modelling resilience in a conditional moment-based framework (Barrett and Constas, 2014; see below the section on resilience as a normative condition approach). In section 5, we will argue this is the most appropriate theoretical framework to model resilience to food and nutrition insecurity.

[15] For example, the UN and the World Bank set up the "New way of working" to deliver the nexus approach. The OECD has made the nexus a priority and members of OECD's Development Assistance Committee

Resilience Measurement Technical Working Group, "In a world where conventional approaches to dealing with humanitarian aid and development assistance have been questioned, resilience has captured the attention of many audiences because it provides a new perspective on how to effectively plan for and analyze the effects of shocks and stressors that threaten the wellbeing of vulnerable populations" (Constas *et al.*, 2014a: 4). According to this literature, the idea of resilience holds appeal as (i) it provides a unified response to shocks resulting from catastrophic events and crises, and to the stressors associated with the ongoing exposure to risks that threaten wellbeing, and (ii) it carries the meaning of a generalized ability to respond to an array of threats that have become more difficult to predict (Constas *et al.*, 2014b).

However, there is considerable debate and ambiguity over the nature of resilience (e.g., a state, a capacity, or a condition), its location (e.g., in individuals, communities, or institutions) and the time frame of resilience-relevant responses (e.g., short- or long-term). As a result, typologies of resilience and "shopping lists" of resilience properties abound (Watts, 2016: 263). Even focusing just on the literature specifically dealing with resilience in developing contexts, that is the capacity of an individual or a household to avoid long-lasting negative consequences in terms of wellbeing, we can find different conceptualizations and definitions that highlight theoretical heterogeneity and lead to different measurement methods. In the next section we will focus exclusively of these approaches.

3.2 Resilience approaches

In a recent scoping review, Barrett *et al.* (2021) identify at least three different definitions relevant for the so-called "development resilience" that drive different approaches, namely resilience as *capacity*, resilience as a *return to equilibrium*, and resilience as a *normative condition*[16].

Resilience as capacity

The most common conceptual approach treats resilience as an ex-ante capacity that limits the adverse effects of risk exposure (i.e., stressors) and/or the near- or longer-term consequences of shocks on individual/household wellbeing. This approach, proposed by FAO within the so-called Resilience Indicators for Measurement and Analysis (RIMA) framework (FAO, 2016), sees resilience as the "capacity that ensures stressors and shocks do not have long-lasting adverse development consequences" (Constas *et al.*, 2014a: 4). Being unobservable, resilience is estimated as a latent variable through the so-called resilience capacity index (RCI), that captures the effects of some combination of observable and unobservable attributes – of an individual, household, community, or more aggregate unit – in a two-step procedure (Alinovi *et al.*, 2008, 2010; d'Errico *et al.*, 2018). In the first step, factor analysis is used to identify the attributes – called "pillars" in the RIMA framework: Access to Basic Services (ABS), Assets (AST), Social Safety Nets (SSN) and Adaptive Capacity (AC) – that contribute to household resilience, starting from observed variables.[17] The factors considered as contributors to each pillar were only those able to explain at least 95% of the variance. In the second step, a Multiple Indicators Multiple Causes model (Bollen *et al.*, 2010) was used, specifying the relationships between the unobservable latent variable (RCI), a set of outcome indicators (FNS indicators,) and the attributes (pillars):

$$RCI=[\beta_1,\beta_2,\ldots,\beta_n]\cdot[ABS,AST,SSN,AC]+\varepsilon_1 \quad (10)$$

and

$$[W_1,W_2,\ldots,W_n]=[\alpha_1,\alpha_2,\ldots,\alpha_n]\cdot RCI\cdot[\varepsilon_2,\varepsilon_3,\ldots,\varepsilon_n] \quad (11)$$

where ε_i are error terms.

The approach proposed by TANGO International (Smith and Frankenberger, 2018) is similar to FAO's in so far it operationalizes resilience as a latent capacity through reduction of a multidimensional set of variables to a resilience index by means of data reduction methods. This approach estimates a RCI based on factor analysis on a wide range of indicators to estimate three latent variables: absorptive, adaptive, and transformative capacities. Absorptive capacities seek to mitigate the impact of shocks and include the availability of assets

are showing some signs of changing how they fund programs. It also has strong relevance to the UN Development System Reform. All UN agencies and many donors and multi-mandated NGOs are supportive of this approach.

[16] A fourth definition is resilience as transformation as emphasized in the literature on socio-ecological systems (Walker *et al.*, 2004; Reyers *et al.*, 2018) that views transformability as a key feature of resilience reflecting the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable.

[17] Informed by previous research on resilience, vulnerability and food security, RIMA also proposes the set of variables comprised in each pillar, such as: (i) schools, health centers, markets, water, electric grid for access to basic services (ABS); (ii) productive (e.g. land, livestock, agricultural equipment,, etc.) or non-productive (e.g. house, other real estate properties) assets (AST); (iii) transfers (e.g. cash or in-kind), formal and informal insurance mechanisms, etc. for social safety nets (SSN); and (iv) access to institutions and networks, diversification of livelihood sources, etc. for adaptive capacity (AC).

and savings. Adaptive capacities spread risk by diversifying livelihoods and relying on social safety nets. Transformative capacities seek to change the underlying dynamics, for example, by improving governance, improving access to markets or empowering women.

As self-evident from the above formalization, the resilience capacity is treated as an explanatory variable of the final outcome (e.g., FNS). Specifically, RCI is a variable that helps explaining variations in the wellbeing outcome, that is a proxy that mediates the negative impact of shocks and stressors rather than an outcome per se. This is important because the many interventions that aim to build resilience necessitate a conceptualization and measure of resilience that can serve as an outcome, in order to evaluate whether resilience is indeed increasing among beneficiaries of a given intervention.

Resilience as return to equilibrium

A second approach conceptualizes resilience as return to equilibrium, that is it assesses whether households have the capacity to recover, sometimes how fast is the speed of recovery, from a shock (Pimm, 1984; Constas *et al.* 2014a; Knippenberg *et al.*, 2019). It describes a condition, i.e. ex-post recovery from shocks, of a wellbeing variable of interest rather than attempting to explicitly model the various capacities that result in rapid recovery. Following Knippenberger *et al.* (2019) notation, let's denote two states $Z^s_{i,t}\in\{0,1\}$ reflecting whether household i is experiencing the adverse effects of a shock s that hit the household in period t-1, with $Z^s_{i,t}=1$ if it has not recovered and $Z^s_{i,t}=0$ if it has fully recovered. Given these two states, i.e. experiencing and not experiencing shock s, the probability of passing from state k to state j is a Markov process: $Pr(Z^s_{i,t-1}=j|Z^s_{i,t}=k)=p_{i,kj}$ where $k,j\in\{0,1\}$. To estimate shock persistence, an auto-regressive linear probability model with one lag can be used:

$$Z^s_{i,t} = \gamma_0 + \gamma^s_1 Z^s_{i,t-1} + \gamma^s_t\left(Z^s_{i,t-1}\delta_t\right) + \delta_t + \mu^s_i + \delta\varepsilon_{i,t} \quad (12)$$

where γ^s_1 conditions the perceived shock, s, on previously experiencing shocks, γ^s_t allows this persistence to vary by periods, δ_t is a time fixed effect and μ^s_i is a household fixed effect.

This conceptualization of resilience is closer to the concept of resilience as used in ecology[18] and engineering that emphasize the capacity to bounce back to the initial state. Differently from the RCI methods, it describes a condition, i.e. ex-post recovery from shocks, of a wellbeing variable of interest rather than attempting to explicitly model the various capacities that eventually result in recovery from the shocks. However, this may not be enough for the use of resilience in development practice, where scholars and practitioners usually deal with undesirable initial states such as poverty or food insecurity. In other words, "development resilience"[19] should not be seen just as a mere return to a pre-shock equilibrium without considering whether that ex-ante state was desirable or not.

Resilience as a normative condition

The fact that development resilience needs to address a normatively undesirable initial state is explicitly considered by the third approach that conceptualizes resilience as a construct measured with reference to a normative wellbeing anchoring (Barrett and Constas, 2014), that is a condition that reflects one's capacity to avoid adverse wellbeing states, rather than a capacity itself. Cissé and Barrett (2018) translate this conceptualization into an econometric strategy that estimates resilience as a conditional probability of satisfying some normative standard of living, such as a minimum herd size, per capita expenditures level, food consumption score, etc. This is done in a three-step procedure, as follows:

a) first, the household-specific conditional mean of a wellbeing indicator (e.g., the food consumption score, FCS) is estimated through a multivariate regression:

$$W_{i,t} = \sum_k \alpha_k W^k_{i,t-1} + \gamma \boldsymbol{X}_{i,t} + \theta \boldsymbol{S}_{i,t} + \varepsilon_{i,t} \quad (13)$$

where, the superscript k indicates the polynomial order to allow for possible non-linear dynamics under a first-order Markov process assumption as in the poverty trap literature (Carter and Barrett, 2006; Barrett and Carter, 2013); $\boldsymbol{X}$ is a vector of time-varying household and community characteristics; $\boldsymbol{S}$ is a vector of shocks or stressors (e.g., climate, price, health, etc.), and $\varepsilon_{i,t}$ are residuals;

[18] In the sense of Pimm (1984) that captures the speed of return to equilibrium following perturbation, but not in Holling's (1973) formulation that conceptualizes resilience as the size of a disturbance needed to dislodge a system from its stability domain.

[19] As clearly stated by Barrett and Constas (2014: 2): "Unlike the term's use in engineering or ecology, where resilience refers to properties of objects or systems and is neither good nor bad, it is merely descriptive, development resilience has clear normative foundations: More is better. Conceptualized in this way, development resilience concerns the stochastic dynamics of human wellbeing and is a worthy goal for development agencies because it varies inversely with the likelihood of being and remaining poor."

b) then, using the residuals of Eq. 13, and regressing them on the same or potentially other regressors, the household-specific conditional variance of the same wellbeing indicator is estimated:

$$\varepsilon_{i,t}^2 = \sum_k \beta_k W_{i,t-1}^k + \delta \boldsymbol{X}_{i,t} + \vartheta \boldsymbol{S}_{i,t} + u_{i,t} \quad (14)$$

where, $u_{i,t}$ are residuals;

c) finally, using the above conditional moment estimates and assuming a two-parameter distribution (e.g., beta, exponential, gamma, normal, etc.) the conditional probability of satisfying some normative wellbeing standard $\underline{W}$ (e.g., at least a non-poor FCS level) in any n time period in the future, called "resilience score" by Cissé and Barrett (2018), is estimated:

$$\rho_{i,n} \equiv Pr(W_{i,n\text{-}1}, X_{i,n}, S_{i,n}) = F(\underline{W}, \widehat{W}_{i,n}(W_{i,n\text{-}1}, X_{i,n}, S_{i,n}), \hat{\varepsilon}_{i,n}^2(W_{i,n\text{-}1}, X_{i,n}, S_{i,n})) \quad (15)$$

where, $F(\cdot)$ is the assumed two-parameter inverse cumulative density function.

Studies that conceptualize resilience as a normative condition treat the resulting measure as an outcome. This has made it popular among academics doing impact evaluation (Phadera *et al.*, 2019; Premand and Stoeffler, 2020) or trying to describe the resilience of distinct populations as the estimated measure provides clear insights on resilience change, makes possible comparisons across sub-populations, and can be aggregated from individual or household level into community, region, or national resilience indicators.[20]

3.3. Empirical evidence

Being a relatively novel field of study, it is no wonder that most of the empirical literature on resilience has developed over the last years, with half of them published from 2016 on (Barrett *et al.*, 2021). Focusing on studies providing quantitative estimates of household resilience to food insecurity[21], the previous section highlights how different definitions drive devising different estimation methods. Some of them, such as the ones based on the conceptualization of resilience as capacity, use ad hoc empirical estimation strategies that are not well-rooted in theory. More generally, almost all studies do not employ credible causal identification methods.

In terms of the contents of the empirical applications, generally most studies aim at illustrating the properties of the resilience measure and findings about the population under study. However, the differences in the approaches – e.g., resilience as capacity vs. resilience as a normative condition – imply different objectives and results of the empirical applications. For instance, the studies adopting the resilience as capacity approaches generally show that households with higher resilience capacity tend to have less child malnutrition and better food security status (Ansah *et al.*, 2019). Furthermore, some studies adopting the resilience as capacity approach (d'Errico *et al.*, 2018; Smith and Frankenberger, 2018; Brück *et al.*, 2019) estimate the RCI and then test its association with the period-on-period change in the FNS indicators. They generally found that a higher RCI is associated with lower near-term impacts of shocks and higher levels of future food consumption. Specifically, d'Errico *et al.* (2018) found that household RCI is positively related to future household FNS outcomes, decreasing the probability of suffering a future FNS loss and facilitating the recovery after the occurrence of a loss in Tanzania and Uganda,[22] whereas d'Errico *et al.* (2019) identify critical heterogeneous resilience thresholds to temperature anomalies in Tanzania based on RCI. Smith and Frankenberger (2018) found suggestive evidence that social and human capital, exposure to information, asset holdings, livelihood diversity, safety nets, access to markets and services, women's empowerment, governance, and psycho-social capabilities such as aspirations and confidence to adapt, all contribute to reduce the negative impact of flooding on household food security in Bangladesh.

Vice versa, the studies adopting the conditional moment-based approach are more interested in assessing the impact of specific conditions of population groups or interventions to targeted populations on their own resilience level. Being highly data-demanding, this approach has only recently been applied to a few countries in Sub-Saharan Africa (Cissé and Barrett, 2018; Knippenberg *et al.*, 2019; Phadera *et al.*, 2019; Premand and Stoeffler, 2020; Abay *et al.*, 2022), proving to be able to predict the individual's probability of not meeting a normatively-established threshold in the future, being decomposable among groups, and suitable to inform targeting adjusting between exclusion and inclusion errors. From the viewpoint of policy implications, most of these studies focuses on the relationship between social protection programs and resilience. In particular, Phadera *et al.* (2019) show that an asset transfer program in Zambia

[20] See Cissé and Barrett (2018) for details.

[21] The resilience literature provides examples of both quantitative and qualitative studies, roughly equally divided among the two categories. Barrett *et al.* (2021) in their scoping review of the development resilience literature, briefly reviewed also qualitative studies.

[22] These results are robust to various model specifications and valid for both analyzed countries.

was able to increase mean assets and decrease variance, signaling an upward shift in households' conditional asset distributions. Similarly, Premand and Stoeffler (2020) found that a cash transfer program targeting poor households in Niger was able to foster resilience by facilitating savings and income smoothing. More recently, Abay *et al.* (2022) show that productive safety net program in Ethiopia is positively associated with resilience the higher and the longer the transfers to households. Furthermore, combining safety nets with income generating or asset building initiatives increases the effectiveness of the interventions. However, short-term (consumption) and longer-term (resilience) outcomes are likely to be driven by different factors, suggesting that optimizing intervention designs for improving short-term welfare may not necessarily improve households' resilience, and vice versa.

Considering strengths and weaknesses of all proposed approaches, the conditional moment-based approach (Cissé and Barrett, 2018) shows clear advantages from the theoretical viewpoint vis-à-vis the other resilience approaches. In fact, the resilience score estimated using the moments-based approach is normatively anchored, it is easy to interpret being a probability, it can be aggregated across / decomposed between subpopulations (such as the well-known Foster-Greer-Thorbecke poverty measures) and it offers the possibility to set different thresholds (e.g. low probability to be above a high threshold vs. high probability to be below a low threshold) thus providing useful information for minimizing the exclusion or the inclusion error in targeting interventions.

However, from the practical viewpoint a recent assessment comparing RCI-like measures, such as the ones proposed by FAO (2016) and Tango international (Smith and Frankenberger, 2018), and the resilience score (Cissé and Barrett, 2018) concludes that "none of the measures consistently outperforms the far simpler approach of using the most recent value of the relevant wellbeing measure to predict the future value of that same variable" (Upton *et al.*, 2022: 13). There is still a lot to do in empirical research to improve the modest out-of-sample predictive accuracy of resilience measures as applied to FNS outcomes.

4. VULNERABILITY AND RESILIENCE AS TOOLS FOR FNS ANALYSIS

Despite the attempts mentioned above to adapt the existing measures of resilience/vulnerability to the analysis of FNS, we still lack a unified framework of vulnerability and resilience to FNS. To pursue this objective, we need first to define what FNS is about. This initial step is critically important because it frames the context against which the vulnerability and resilience concepts can be assessed as useful tools for applied analysis, i.e. gauging insights on how to measure FNS, monitoring the impact of its determinants (including different shocks and stressors), assessing progress towards FNS, designing interventions, and targeting policies.

According to FAO, food security exists if and only if "all people at all times have physical, social, and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (World Food Summit, 1996). Analyzing this definition it is clear that "all people" refers to any social group, focusing primarily on the most vulnerable ones (e.g., children, the elderly, pregnant and lactating women, the poor, etc.); "at all times" refers to both short and long-run FNS problems, highlighting the need to reduce food consumption volatility over time; "access" emphasizes that the key dimension ensuring FNS is a relational dimension that links the utilization of food by consumers with the availability of food, that can be impaired by physical (e.g., lack of infrastructure), social (e.g., unequal distribution among and within social groups, including the household), and economic (e.g., poverty) factors; the reference to "dietary needs and food preferences" makes clear that consumer sovereignty and the right to food are key in determining FNS, whose ultimate goal is "an active and healthy life".

There is a vast agreement that this definition can be conceptualized as resting on four dimensions – availability, access, utilization, and stability – that are inherently hierarchical, with availability necessary but not sufficient to ensure access, which is in turn necessary but not sufficient for effective utilization, all of them being necessary but not sufficient for stability (Webb *et al.*, 2006).[23] Although FNS measurement has been substantially expanded in recent decades, there persists significant dissatisfaction with existing measurement systems (Barrett, 2010; Headey and Ecker, 2013). To date, no FNS measure can capture all food security dimensions.[24]

[23] As emphasized by Dasgupta and Ray (1986), the hierarchy can also go the other way around especially for very poor people: very low utilization would imply less access and availability because of a poor health status that will not ensure the capacity to gain a livelihood, leading to a nutrition poverty trap.

[24] For instance, food availability measures enable frequent and geographically broad estimates, but at the expense of neglecting waste and the inevitably unequal distribution and uses of food within a population. Conversely, measures based on higher-cost individual and household surveys can associate measures with targetable individual characteristics, offering depth in measuring two or three of the food security dimensions (e.g., commonly, access and utilization).

In practice, analysts use proxy measures for different aspects of FNS, implying that the choice among indicators necessarily involves tradeoffs as each measure highlights and neglects different food security dimensions.[25] As a result, it is the objective of the specific analysis at hand that drives the choice of an indicator.

Nevertheless, there are some general characteristics that an ideal FNS measure must feature. First and foremost, food availability, access to food and its utilization may change over time with risks (Pangaribowo *et al.*, 2013). In other words, households become food insecure when they are unable to mitigate the negative risks associated to food availability, access, and utilization dimensions. A forward-looking framework is essential to capture this dynamics as explicitly suggested by the "at all times" argument of the Word Food Summit FNS definition and captured by the stability dimension. In short, FNS inherently encompasses risks. Unfortunately, this forward-looking framework has been largely missed by current literature except a few isolated cases (Haddad and Frankenberger 2003; Webb *et al.*, 2006; Løvendal and Knowles, 2007). The proposed distinction between chronic food insecurity - defined as the incapacity to cover minimum food needs over the long term – and transitory food insecurity – defined as a temporary incapacity to cover food needs – appears to be misplaced too (Devereux, 2016). While a chronic status is more proximate to a deterministic path (i.e. the structural determinants of food and nutrition insecurity), a temporary incapacity is more linked to shocks and/or misfortune. The strong risk aversion of the poorer households points rather to the long-term impacts of risks and calls for the incompleteness of FNS analyses that do not look adequately at the comprehensive impacts of risk exposure on FNS, that is the need to look at the second moment of the relationship.

This is where vulnerability and resilience come into the picture. In fact, both are genuinely forward-looking, that is they reflect the probabilities of satisfying a given food consumption norm in the future. Furthermore, an ideal FNS measure should be able to capture the heterogeneity of various groups of population, i.e. it should capture the generating process of different FNS and nutrition outcomes (Barrett, 2002) at different scales of analysis, from national to subnational, community, household and individual levels. In short, as emphasized by Upton *et al.* (2016), an ideal FNS measure metric would satisfy four basic axioms:

1. *Scale*: being able to address both individuals and groups at any scale of aggregation, including geographic regions and political jurisdictions (cf. "all people" in the food security definition);
2. *Time*: encompassing both predictable and unpredictable variability over time capturing the "stability" dimension (cf. "at all times" in the food security definition);
3. *Access*: referring to various notions of individual and collective wellbeing, capturing explicitly the "access" dimension and implicitly also the "availability" dimension as a necessary condition for access (cf. "physical, social and economic access" in the food security definition);
4. *Outcome*: focusing on dietary, health, and/or nutrition outcomes is required to capture the "utilization" dimension of food security. (cf. "an active and healthy life" in the food security definition).

To date, no FNS measure satisfies all four axioms. It is worth emphasizing that virtually all currently used proxy measures are inherently static and most of them do not allow aggregation/decomposition of the involved measure. Furthermore, many of them do not cover the utilization dimension. As a result, these measures poorly reflect food security under the World Food Summit definition.

The key question here is whether and to what extent vulnerability and resilience can do a better job than standard FNS measures in assessing who the food insecure are. To answer this question, we will use the four axioms above to critically assess the capacity of the various vulnerability and resilience approaches to reflect food and nutrition security as defined by FAO (Table 1).

Starting from vulnerability measures, they are of course all inherently forward-looking. However, the most commonly applied measure, namely VEP, does not satisfy the time axiom as it rests on a very heroic assumption, that is the cross-sectional variation of the

Table 1. Assessment of vulnerability and resilience approaches to FNS measurement.

Approaches	FNS security measurement axioms			
	Scale	Time	Access	Outcome
Vulnerability				
Expected poverty	Yes	No	Yes	No
Low expected utility	Yes	Yes	Yes	No
Threat to future poverty	No	Yes	Yes	Yes
Resilience				
Capacity	No	No	Yes	Yes
Return to equilibrium	No	Yes	Yes	No
Normative condition	Yes	Yes	Yes	Yes

[25] Thereby subtly influencing prioritization among FNS interventions.

sampled household's consumption is a good proxy of the variation over time of household-specific consumption. At the same time, it falls short also satisfying the outcome axiom in so far a level of consumption above the poverty line – i.e. not being poor – is a necessary but not a sufficient condition for non-deprivation in key dimensions such as nutrition and health. By shifting the focus from achieving a given level of consumption to a measure of risk premium expressed in utility units, VEU sorts out the time axiom but do not explicitly address the outcome axiom. VTP fares better in so far it is risk sensitive and explicitly considers the rate of coverage of basic needs – including the ex-ante risk of becoming food insecure, even if ex-post consumption below a critical norm does not materialize. This in principle could be more proximate to FNS. However, it does not satisfy the scale axiom. In fact, it explicitly takes into account the many different states of nature a given individual is exposed to, which cannot be aggregated across individuals unless very strong hypotheses are met.

Resilience as a capacity explicitly considers various possible FNS indicators and correlates explaining food access. However, this approach falls short in the other two axioms, being not decomposable/aggregable across sub-populations and being not a forward-looking measure. Resilience as return to an equilibrium is forward-looking and can in principle be conditioned to factors that can make the recover from a shock faster or slower, thus satisfying the time and access axioms, respectively. Unfortunately, it is not decomposable/aggregable across sub-populations (scale axiom) and, more importantly, it falls short of fully addressing any nutritional/health norm, focusing only on the capacity of the household/individual to return to the pre-shock status, thus not satisfying the outcome axiom. The resilience as a normative condition is the only approach that can measure FNS in a way that meets all four of the FNS measurement axioms. In fact, by identifying FNS at the individual or household level, the measure is aggregable into higher-level groups (social groups, regions, etc.), thereby satisfying the scale axiom; the approach is explicitly dynamic and forward-looking, thereby satisfying the time axiom; the analyst can condition the moments of the FNS distribution on any of a host of economic, physical, and social factors, thereby satisfying the access axiom; and by using suitable measures of health or nutritional status as dependent variables, this method satisfies also the outcomes axiom.[26]

[26] For an empirical application to Kenyan pastoralist households, using the household dietary diversity score and child mid-upper arm circumference as outcomes, see Upton *et al.* (2016).

5. THE CASE FOR A UNIFYING FRAMEWORK

The analysis carried out above makes clear that vulnerability and resilience share most of the building blocks for an adequate conceptualization of FNS analysis, such as the explicit consideration of risks, stressors and shocks as well as the ability/capacity to detect future and possibly long-lasting adverse welfare consequences, although only the resilience as a normative condition (i.e., the conditional moment-based approach) satisfies all four FNS measurement axioms. On the other hand, it is self-evident that the two concepts, although looking at the same subject – i.e. the effect of risks and shocks on economic agents' wellbeing – and sharing common conceptualization and estimation needs – i.e. the need for a forward-looking analysis in a dynamic stochastic framework – are actually different constructs. Starting from this common ground and keeping in mind the highlighted important differences, we propose a unifying framework able to estimate multiple conditional moments of the same welfare function.

To begin with, let's discuss why vulnerability and resilience are *not* one the flip side of the other. To clarify this, it is useful to refer to a graph originally proposed by Carter *et al.* (2007) in one of the first empirical studies assessing the role of shocks in the emergence of poverty traps (Figure 1). It shows the likely impact of a shock on asset dynamics for two archetypical wealthy and a poor household, A_w and A_p respectively. Moving from the left to the right different phases of this dynamics are highlighted: (i) the pre-shock period (no shaded background); (ii) the time when shock hits the households (darkest gray background), followed by (iii) the coping phase when the households try to smooth the negative effect of shock on consumption through asset decumulation (intermediate gray background), and (iv) the recovery phase (pale gray background) when the household would hopefully be able to rebuild its own asset stock unless it is caught in a poverty trap.

The households' dynamics in absence of shocks is represented by the solid lines in the pre-shock phase and the dashed lines in the subsequent phases.[27] If the households are not / will not be hit by a shock, then they are not vulnerable (V = 0). They are also resilient (R = 1) as they are not affected by risks or shocks that can drive his wellbeing beneath a given normative threshold. The situation is quite different if a shock hits the households. Specifically, when the shock hits a very poor house-

[27] The assumption here, consistently with neoclassical growth theory, is that without shocks there could be a convergence process through which the poor household will be able to accumulate faster than the wealthier household thus catching up with the latter.

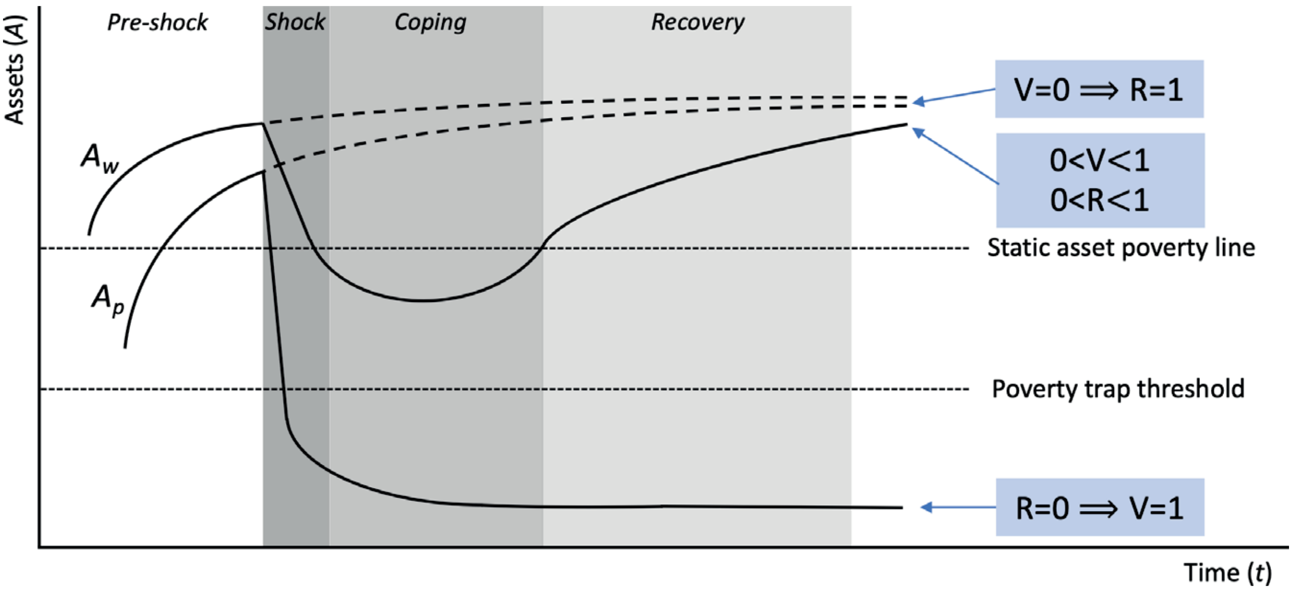

Figure 1. Different household asset dynamics after a shock: vulnerability vs. resilience. Source: Authors' elaboration from Carter *et al.*, 2007.

hold driving it below the poverty trap threshold,[28] this implies the household is not able to recover (R = 0, i.e. it is not resilient) and *a fortiori* this implies that it is vulnerable too (V = 1). However, Figure 1 also shows that there could be intermediate cases where a given household can be both vulnerable and resilient (0 < V < 1 and 0 < R < 1), as shown by the evolution of the asset dynamics of the wealthier household, A_w, that is driven beneath the static asset poverty line by the shock, but is also able to bounce back above the asset poverty line after a period of recovery.[29]

In fact, while vulnerability looks at the probability of an agent's wellbeing falling beneath some normative standard in at least one period in the future, resilience highlights the prospective importance of the non-linear path dynamics. This can be done adopting the poverty traps framework to explore the long-term path of the agent's wellbeing: focusing only on conditional expectations, we can conclude that an agent is expected to be on average dynamically non-poor if she is above the poverty line threshold (i.e., the asset threshold beneath which people fall into a poverty trap, see Carter and Barrett, 2006). However, if instead of looking only at conditional expectation we consider also conditional variance, it might be that the agent would be both vulnerable (e.g., becoming food insecure) and resilient (e.g., because food insecurity is sufficiently low in duration, intensity, and/or likelihood).

To show this, let's look at Figure 2, that represents the reduced form of one possible conditional expectation function of household wellbeing, where today's wellbeing appears on the horizontal axis and tomorrow's expected wellbeing on the vertical axis. The dashed 45° line represents points where standards of living are not expected to change over time (i.e., dynamic equilibria or stable states). Following Barrett and Constas (2014), three distinct regimes (and equilibria) can be identified: (i) a humanitarian emergency area, within which the agent is bound to collapse toward death, D; (ii) a chronic food insecurity area, within which people recover from shocks, either adverse or favorable, to a stable but food and nutrition insecure status, I; and (iii) a food and nutrition security area, within which people are expected to recover from non-catastrophic shocks leading to a food and nutrition secure equilibrium, S. These three

[28] The poverty trap threshold has been dubbed by Zimmerman and Carter (2003) as the "Micawber threshold" (borrowing it from Lipton, 1993), after the Dickens' character who was a perpetually insolvent debtor with whom David Copperfield took up residence, who moves in and out of different jobs and debtor's prison, unable to advance his own standards of living. The Micawber threshold is a *dynamic* asset poverty threshold according to which households whose assets place them above it would be expected to escape poverty over time, while those below it would not.

[29] A consistent outcome can be derived by looking at consumption behavior – that is the flip side of this asset behavior – by adopting a structural framework such as that proposed by Elbers and Gunning (2003). In this framework, resilient but vulnerable households can be identified by looking at the long-term non-linear consumption dynamics under risk, taking simultaneously into account their risk exposure and their consumption smoothing behavior through changes in assets. This allows to compute, for each time period, households' vulnerability as a function of various sources of heterogeneity – primarily, initial assets but also differences in risk exposure – and correctly track a non-poor individual or household with a high second conditional moment in her expected path dynamics as both vulnerable and resilient.

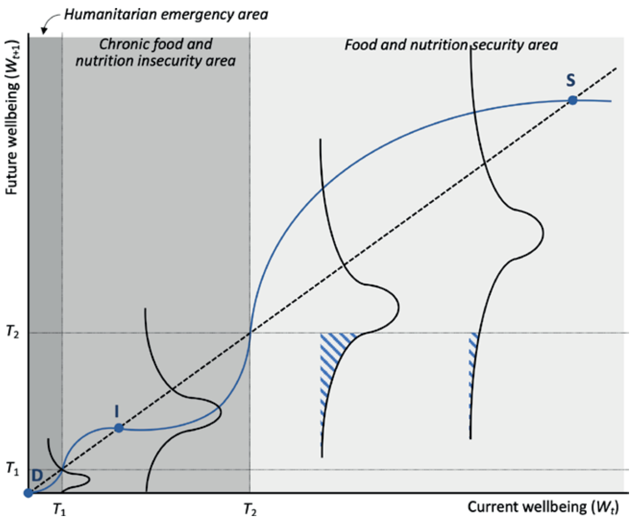

Figure 2. Non-linear expected wellbeing dynamics with conditional transition distributions. Source: Authors' elaboration from Barrett and Constas, 2014.

regimes are separated by two thresholds, T_1 and T_2, that separate the basins of attraction defined with reference to initial period wellbeing levels expected to lead toward a dynamic equilibrium in the relevant range due to agents' expected behaviors. The non-linear expected wellbeing dynamics is represented by the the expected livelihood function (i.e., the curve swinging around the dashed diagonal): it identifies multiple stable states (i.e., death, non-FNS, and FNS equilibria) as well as thresholds separating the different basins of attraction (i.e., T_1 and T_2).

Looking just at conditional expectation, as the poverty trap literature usually does, what counts is just the initial state, W_t, that determines the expected future wellbeing state, W_{t+1}. However, we cannot rule out that a negative shock hitting an agent who is above the poverty trap threshold, even if associate with a very low likelihood (represented in Figure 2 by the dashed areas under the conditional transition distribution functions associated to the conditional expectation function), can bring that agent beneath the normative established threshold (e.g. a certain level of food intake) for some periods t in the future, thus determining a welfare loss (in this case, she will be also recorded as vulnerable). Furthermore, the same shock can modify the process through which stocks of assets (e.g., land) and flows of inputs (e.g. labor) can generate flows of income or other goods or services of value (e.g., farm output, time spent with friends, etc.). That is, the structure of this process (i.e., the shape of the expected livelihood function) can change. This also can determine a welfare loss as compared to the pre-shock situation. Resilience as a normative condition (Cissé and Barrett, 2018) records these potentially non-linear dynamics of shock-induced welfare changes, estimating what is the conditional probability of being at or above a given normative standard at some point t in the future.

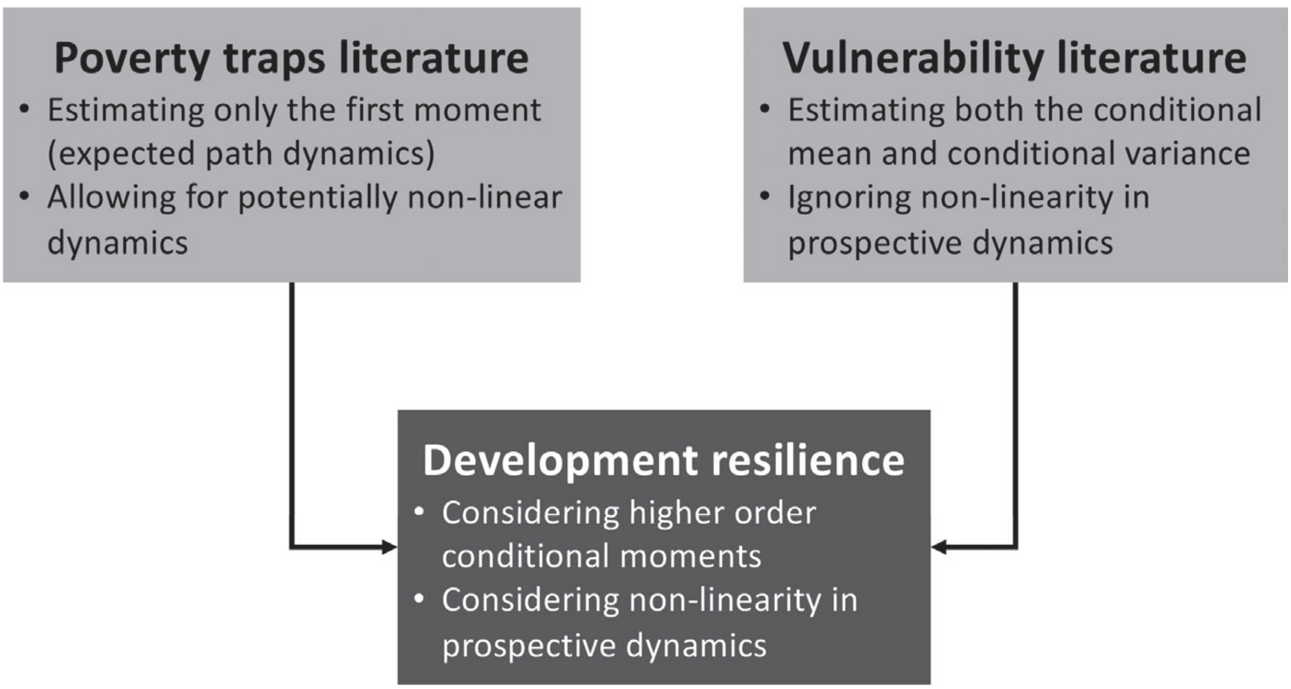

Figure 3. Conditional moments-based resilience as a unifying framework.

If and only if this probability (i.e., the resilience score, see Eq. 15) is higher than a normatively established minimal threshold probability (i.e., an acceptably high level of probability of being food secure), we can classify that agent as resilient. The flip side of this would be a potentially non-linear time-varying measure of vulnerability, using the time sequence of resilience estimates to estimate transition probabilities into or out of poverty conditional on one's characteristics, risk exposure and immediate pre- and post-shock welfare measures.

Unfortunately, the vulnerability literature generally does not allow for such a non-linear dynamics. At the best of our knowledge, the only paper estimating vulnerability in a framework of non-linear dynamics is Elbers and Gunning (2003). They used a stochastic Ramsey model to find the household optimal welfare measuring vulnerability as the shortfall from the welfare attained if the household consumed permanently at the poverty line (see, also, Elbers *et al.*, 2007). Unfortunately, the data needed to estimate such a structural dynamic model are often not available in developing contexts.

All the above emphasizes the need to consider the contributions of different strands of literature to reach a unified framework for a comprehensive, forward-looking analysis of food and nutrition security. Specifically, we need to draw on the poverty traps literature to include potentially non-linear path dynamics and asset-based poverty traps; at the same time, we need to leverage on the vulnerability literature to get a forward-looking, probabilistic measure of wellbeing accounting for both conditional means and conditional variance. In this respect, the resilience conditional moment-based approach proposed by Cissè and Barrett (2018) emerges as a possible unifying concept to effectively and comprehensively assess food and nutrition security (Figure 3): on the one hand, the vulnerability literature emphasizes the need to estimate both the conditional mean and conditional variance, but it ignores non-linearity in prospective dynamics; on the other hand, the poverty trap literature allows for potentially non-linear dynamics but estimates only the first moment (expected path dynamics). The development resilience conceptualization (Barrett and Constas, 2014; Cissé and Barrett, 2018) borrows on both strands of literature considering higher order conditional moments (as vulnerability does) and non-linearity in prospective dynamics (as poverty traps do).

6. CONCLUSIONS AND RECOMMENDATIONS

This paper aims at answering a key research question: how leveraging the existing knowledge to improve ex-ante targeting of households vulnerable to food and nutrition insecurity and to enhance the effectiveness of interventions aiming at building resilience. In order to answer to this question, we reviewed the literature on conceptualization and empirical measurement of vulnerability and resilience with specific reference to food insecurity. Building on these strands of literature, our answer is twofold: first, we need to operationalize a single, unified framework able to estimate multiple conditional moments of the same welfare function, including potentially non-linear path dynamics, to assess forward-looking, probabilistic measures of food insecurity able to satisfy a specific set of axioms (i.e., suited for targeting and program evaluation); second, we need to acknowledge what are the main limitations of current analyses and propose a clear roadmap for improvement.

We argue that clarifying the relationships between vulnerability and resilience helps providing a better suited and more comprehensive framework for FNS analysis as anticipated by Cissé and Barrett (2018) in proposing the so-called "development resilience" framework. In fact, from the conceptual viewpoint, this framework makes possible to integrate some valuable features of the vulnerability and poverty traps concepts into implementable, theory-based resilience measures. It considers higher-order conditional moments (as vulnerability literature does) and non-linearity in prospective dynamics (as poverty traps literature does). From the practical viewpoint, the nature of the resilience allows for the integration into a single framework relief (i.e., humanitarian) as well as development efforts, putting greater emphasis on longer term preventative measures rather than short-term curative responses. This is particularly important taking into account the current discourse on the human-development-peace nexus as an operational principle guiding international organization/agencies interventions (UNRISD, 2005; UN, 2016). This unified framework also meets the four food security measurement axioms as highlighted by Upton *et al.* (2016).

Looking at the limitations of the approach, we acknowledge that estimating these conditional moments is highly data-demanding, as it requires high-frequency, micro level, good quality panel data, ideally at seasonal frequency, including the entire set of possible covariates and idiosyncratic shocks, that are seldom available especially in developing contexts. On top of this, it should be emphasized that the estimated measures exhibit only modest out-of-sample predictive accuracy, generating many false negative and positive (Upton *et al.*, 2022). Those are the actual Achille's heels of the proposed framework and there is still a lot of work to be done to improve resilience measurement. This calls for alternative data generation strategies as well as investing in some applied research priority areas. Referring to the former, integration with non-conventional data sources (e.g., massive, crowdsourced, citizen-generated data, etc.) appear to be a promising route. However, it also needs reaching better quality standards to be properly linked to survey data (Carletto, 2021). As a result, the analysis of the data gaps and the promotion of complementarity and interoperability between old and new data sources is one of the key missing links for the operationalization of a truly unified framework.

In terms of a future applied research agenda, the first recommendation is methodological and calls for producing more accurate measures of vulnerability and resilience to food insecurity increasingly inspired by the depicted common unified framework. A second recommendation refers to expand the geographical coverage as well as the range of shocks and stressors considered, focusing on areas that have been relatively neglected by the studies carried out so far such as the rigorous evaluation of resilience-building interventions impacts (e.g., specific asset transfers vs. provision of public goods such as irrigation schemes or transport infrastructure, etc.), and exploring the relationships between measures at different levels of analysis such as individuals, households, communities and higher geography levels.

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The local economic impact of climate change mitigation in agriculture

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Abstract. Greenhouse gas (GHG) mitigation measures are currently being implemented in the agricultural sector across the globe. Questions have been raised about the distributional and spatial impacts of agricultural emissions mitigation policies, especially at the local level. This study examines the local impact of a low-income farming sector, beef farming, in a typical Irish beef farming county, County Clare. Input-output analysis reveals that Clare beef farmers purchase the vast majority of farm inputs within the county, with intra-county suppliers providing 90% of their inputs and overheads. We examine the impact of reducing the size of the beef herd in Co. Clare as a direct consequence of meeting national GHG emissions targets by 2030. Taking direct, indirect, and induced effects together, there is an €18.4 million reduction in economic activity in 2030 following the decrease in the beef herd with €14.72 million of that reduction taking place within the Mid-West region.

Keywords: GHG Mitigation, Agricultural economics, Input-output modelling, Microsimulation.
JEL Codes: Q12, Q18, Q58, R15.

HIGHLIGHTS

- Irish beef farmers are highly dependent on local markets for inputs.
- GHG mitigation measures reducing herd size will heavily impact the local economy.
- Including multipliers, the overall economic loss is almost double the direct loss.

1. INTRODUCTION

Many countries are currently instituting policies to reduce their emission of greenhouse gases (GHG) in order to mitigate against climate change[1].

[1] Climate change mitigation is defined as a human intervention to reduce emissions or enhance the sinks of greenhouse gases (IPCC, 2018).

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In the European Union (EU), the European Green Deal aims to reduce net GHG emissions by at least 55% from 1990 levels by the year 2030, and to achieve net zero emissions by 2050 (European Commission, 2019). In Ireland, the 2021 Climate Action Plan provides a detailed plan for to achieve a 51% reduction in overall GHG emissions by 2030, with the aim of reaching net zero emissions by no later than 2050 (Government of Ireland, 2021).

Due to the historic importance of agriculture relative to other industries in Ireland, the agricultural sector is the single largest contributor to overall GHG emissions, accounting for 37.1% of emissions in 2020 (EPA, 2021). This compares with a figure of just over 10% for agricultural emissions in the EU as a whole (Mielcarek-Bocheńska & Rzeźnik, 2021). To meet abatement targets, the levels of GHGs intrinsic to agricultural production such as methane (CH4) and nitrous oxide (N2O) will need to be addressed.

However, questions have been raised about the distributional impacts of agricultural emissions mitigation policies, especially those that rely on the "polluter pays" principle, the effectiveness of which stems from the contraction of output that they induce, by reducing profits and causing farms to exit the sector (OECD, 2019). Polluter pays measures, such as pure carbon taxes, have generally been shown to be regressive, harming lower income households more than higher income ones (Wang *et al.*, 2016; Verde & Tol, 2009). Within agriculture, mitigation measures[2] that affect farms directly, or indirectly through increased input costs, are more likely to affect poorer farm households and lead to farm exit (Mosnier *et al.*, 2017) and may be ineffective in abating agricultural nonpoint pollution (Kahil & Albiac, 2013).

Agriculture is not just varied in terms of levels of farm income but also with regard to space. Soils, weather, and other agronomic conditions differ across space, influencing yields, agricultural outcomes, and choice of farming activity (O'Donoghue *et al.*, 2015). As farming in Ireland has become more specialised, local conditions have done much to determine which farming activity dominates in each area (Gillmor, 1987). Therefore, emissions mitigation measures that particular impact specific types of farming are likely to have an outsized impact in areas where that type of farming is dominant.

This paper examines the economic and environmental effect of agricultural emissions mitigation measures at a local level. We focus on Ireland as a country with a significant agri-food sector and ambitious targets in terms of reducing GHG emissions in the near future. Ireland has a significant agricultural footprint with about two-thirds of its land devoted to agricultural use. Agri-food is the largest indigenous business and accounted for 6.7% of GNI* in 2019 (DAFM, 2020). Spatially, the better quality agricultural land can generally be found in the south and east with the poorer land in the north and west (Frawley & Commins, 1996). The most profitable sub-sectors within agriculture, dairy, and to some extent, tillage farming, are predominantly concentrated in the south and east. The lower margin beef and sheep sectors are to a large extent located in the midlands, north and west of the country.

In this paper we focus on beef cattle farming which is the most widely practiced form of farming in Ireland. To examine the local impact of mitigation measures, we concentrate on beef farming in one county, Co. Clare in the west of the country. In general, farming in the county is not considered suitable for intensive production with 94% of the agricultural area classified as severely disadvantaged (DAFM, 2022).

The Irish government's agri-food strategy, Food Vision 2030, published in 2021, commits to a minimum 10% reduction in biogenic methane by the year 2030 (DAFM, 20201). Given the heterogenous nature of farming in Ireland, the implementation of a national level target such as this may have differential impacts across the country. This paper examines the impact of a 10% methane reduction on cattle beef farming in Co. Clare, taking account of the interlinkages between cattle beef farming and the local economy. This is accomplished by using spatial microsimulation to create a detailed dataset for local farmers and simulating the economic effect using input-output modelling of a reduction in the beef cattle herd in Co. Clare resulting from meeting the methane reduction target.

Moretti (2010) highlights the impact of changes in tradeable sectors on jobs in non-tradeable sectors. The agri-food sector is an example of a sector with potentially large local impacts in terms of local feed, animal, and service inputs, but is also part of a major globally traded system. Linkages can be relatively complex. Harriss (1987) finds that in addition to production impacts, consumption impacts can be even higher if a stronger agricultural sector reduces outward migration from a rural area. The effects of local spillovers from agriculture in the literature are relatively mixed. Santangelo (2016) finds evidence of positive spillovers from agriculture on the wider local economy in both the agriculture and non-agricultural areas, while Hornbeck and Keskin (2015) find local gains within the agricultural sector but

[2] Mitigation measures are technologies, processes or practices that contribute to mitigation, for example, renewable energy technologies, waste minimization processes and public transport commuting practices (IPCC, 2018).

limited gains elsewhere from an exogenous change on the sector via improved irrigation.

This is a novel piece of research in an Irish or European context. While previous studies such as Miller *et al.* (2014a) have examined the multiplier effects of agricultural output changes at a national level, few studies have examined the multiplier effects of output changes at a local level. There is also a gap in the literature with regards to the interaction between farm households and the local economy (Roberts *et al.*, 2013). The local economic impacts of nationally implemented GHG mitigation measures are also understudied in the literature. This is particularly relevant for livestock farming due to its emissions intensity and localised nature. In 2019, agriculture accounted for 1.9% of economic output in the EU-27, yet generated 15.6% of EU-27 GHG emissions, the second largest industrial share (Giannakis & Zittis, 2021). This is mainly due to beef and dairy production, which have significantly higher GHG emissions per euro of economic output than other agricultural sectors or aquaculture (Tsakiridis *et al.*, 2020).

Like Ireland, many European countries have regionalised livestock production, with specific regions specialising in beef and dairy farming. Examples include Wallonia in Belgium (Duluins *et al.*, 2022), Massif Central and Pays de la Loire in France (Balouzat *et al.*, 2020), and Galicia in northern Spain (Lomba *et al.*, 2022). Agricultural systems in these areas are frequently embedded in local value chains, with many inputs being sourced locally and outputs being processed within the region (Vázquez-González *et al.*, 2021; Pays de la Loire Regional Council, 2019). As a result, mitigation measures to reduce agricultural GHG emissions are likely to have an outsized economic impact in these regions due to value chain linkages. This study looks to provide evidence of the extent of that economic impact at a local level.

Additionally, this research applies a microsimulation approach to modelling the local economic impact. Microsimulation models have previously been applied in a spatial context to examine the multiplier effects of major job losses or gains at a local level (Ballas *et al.*, 2006a), the implications of CAP reform for the national spatial strategy (Ballas *et al.*, 2006b) and the local impact of the marine sector in Ireland (Morrissey *et al.*, 2014).

In the next section, we describe the background regarding the local economic impact of agriculture and the related literature. The methodology is described in section 3 followed by a description of the data sources. This is followed by three separate results sections, the first dealing with the spatial distribution of farms and farm income in the county, the second set of results dealing with the spatial distribution of livestock sales and the source location of inputs and the final results section dealing with the environmental impact of a reduction in the beef cattle herd and local multipliers. This is followed finally by the discussion and conclusions.

2. BACKGROUND

Cattle farming is the most prevalent form of farming in Ireland, accounting for 47% of agricultural land use in 2011 (Geoghegan & O'Donoghue, 2018). Cattle farmers in Ireland are highly dependent on publicly funded subsidies and have become increasingly vulnerable to a cost-price squeeze with declining margins per volume of beef (O'Donoghue, 2013; Hennessy *et al.*, 2008). Evidence suggests that many cattle farmers use subsidies to support loss-making production (Howley *et al.*, 2012). In combination with off-farm income, publicly funded subsidies allow many cattle farms to maintain a reasonable standard of living and be economically sustainable (Hynes & Hennessy, 2012). The retention of these farm households in rural areas supports the relevant local economies via the farm and non-farm expenditures attributed to these households.

Although the economic position of Irish cattle farmers is well covered in the economic literature, there is something of a void in relation to the treatment of the local economic effects of cattle farming production. Cattle farmers may not enjoy the profitability of their dairy farming counterparts, but they do contribute indirectly towards other economic activity in rural Ireland. The concept of 'good farmers' should account for the local social and economic outputs that farmers provide (Sutherland & Burton, 2011). Miller *et al.* (2014b) have developed a social accounting matrix to examine the wider economy effects of a decline in the beef sector and show that significant employment losses in the wider economy would result. The analysis is focused however, at a national rather than local or regional level.

The inadequate treatment of the wider local economic effects of agriculture in Ireland contrasts with the United States where numerous studies have examined this issue. Foltz and Zeuli (2005) find that small farms are more likely to purchase inputs locally in communities where an array of marketing outlets exist. In a study of Wisconsin dairy farmers, Lambert *et al.* (2009) find that farmers located in areas with relatively large farm populations appear to be better served by local input suppliers indicating that farm-community linkages are strongest where farms are numerous and where the sector is large enough to anchor a regional farm supply centre.

Aside from specific farming activities, farmers also contribute directly to local economies through off-farm employment. In Ireland, a relatively high proportion of Irish cattle farmers engage in off-farm employment, with 40 per cent of cattle farms operators being employed off-farm (Donnellan *et al.*, 2020). Pluriactivity is therefore likely to play an important role in determining the economic welfare of cattle farming households. Shucksmith and Ronningen (2011) argue that small farm holdings provide a base from which rural households are able to sustain their livelihoods through pluriactivity, keeping 'lights in the windows' and retaining populations in areas from which they would surely have been lost in the case of farm amalgamation.

While the ability of mitigation measures to reduce GHG emissions in agriculture has been much discussed in the literature, the potential trade-offs between economic and environmental concerns in agriculture, especially at a local level, have not been as well studied. Some national-level studies have been performed, making use of economic analysis models such as input-output (IO) and computable general equilibrium (CGE) modelling. Like Ireland, Brazil's biggest source of GHG emissions is from the agricultural sector. Using a national-level IO model, De Souza *et al.* (2016) find that an overall 1% reduction in Brazilian GHG emissions would fall heaviest on the livestock sector, which in turn, would greatly impact poor households who rely on livestock as their main source of income. Wu *et al.* (2015) use a CGE model to simulate the effect of a GHG emissions intensity levy imposed on the agri-food sector in Northern Ireland. They find that without the adoption of feasible technology, there is a risk of serious damage to agri-food competitiveness with relatively limited economy-wide environmental gain, leading to trade diversion and GHG emission leakages. Bourne *et al.* (2012) use a CGE model to examine the potential impact of Kyoto and EU environmental policy targets on specific agricultural activities in Spain and find a reduction in agricultural output, increased prices for agricultural products and a cumulative fall in agricultural incomes of €1.5 billon compared with a business-as-usual scenario. Research from Chile by Mardones and Lipski (2020) shows that a CGE-modelled environmental tax applied only to the agricultural sector results in a sectoral contraction and a generalised increase in the production of all other sectors, without a substantial fall in overall GHG emissions.

In addressing the local economic effects of agriculture, researchers have focused analysis on a relatively small geographical area e.g., a particular district within New York state in Jablonski and Schmit (2014) and Wisconsin dairy communities in Foltz *et al.* (2002). This approach can be justified on the basis of data collection costs and the desire for a relatively homogenous sample of farms. Our analysis is focused on the cattle sector in a particular area of Ireland, Co. Clare. This county is chosen as cattle farming is overwhelmingly the most important agricultural enterprise in the county. According to the 2010 Census of Agriculture, approximately 78 per cent of farms in County Clare are classified as specialist beef production which far exceeds the national average of 56 per cent.

3. METHODOLOGY

The objective of this study is to model the impact of cattle farming on the local economy. This objective has a number of methodological challenges. While good micro farm level data exist containing incomes, costs, and technical attributes at national level and while there exists spatial census information in relation to small area statistics of farm structures, no dataset contains both detailed income sources and fine spatial attributes. It is therefore necessary to utilise a methodology to synthetically generate spatially differentiated, micro data.

One methodology that allows us to simulate the necessary data is spatial microsimulation (O'Donoghue *et al.*, 2014). Hynes *et al.* (2009a) outline three main benefits of using synthetic data: the ability to create micro data from aggregated macro data at different spatial resolutions; the ability to retain a number of characteristics of micro units within the data and facilitate a multivariate analysis; and the ability to assess the impact of policies on particular groups within the population.

The SMILE-FARM model simulates spatially representative households and farms at an electoral district (ED) level using several data sets: the Teagasc National Farm Survey, the Census of Population, and the Census of Agriculture (COA) amongst others (O'Donoghue, 2017). The data simulation process involves the sampling of farms from the micro dataset containing detailed farm level data from the Teagasc NFS to make it consistent with the COA. The constraint variables used include farm size, farm system, soil type, and stocking rate.

The SMILE-FARM model is used in this paper to create an enhanced spatial microsimulation model by combining SMILE-FARM with the farm-level survey information collected for Co. Clare using a quota sampling technique (O'Donoghue *et al.*, 2017). The most recent SMILE-FARM model which is from the year 2014 is combined with the survey data which were collected in the year 2010. Although the two datasets are not contemporaneous, NFS data show that there was relatively little change in the characteristics of cattle farming in Co. Clare over this time period so combining the two datasets is appropriate.

Input-Output

In order to estimate the multiplier effect associated with changes in the size of the beef cattle herd, a sub-regional input-output model is employed. A multi-regional input output (MRIO) model for sub-regions takes the same form as that of a regional MRIO with a multiregional matrix (of technical coefficients. The objective is to capture the various economic transactions between and among the several regions in a multi-regional economy.

A p-region MRIO would be expressed as follows:

$$(I\text{-}A)x=d$$

and the solution for x is shown as follows (similar to the standard I-O solution for x):

$$x=(I\text{-}A)^{-1}d$$

where:

$$A = \begin{bmatrix} A^{11} & 0 & \cdots & A^{1p} \\ A^{21} & A^{22} & \cdots & A^{2p} \\ \vdots & \vdots & \ddots & \vdots \\ A^{p1} & 0 & \cdots & A^{pp} \end{bmatrix}, I = \begin{bmatrix} I & 0 & 0 \\ 0 & I & 0 \\ \vdots & .. & \vdots \\ 0 & 0 & I \end{bmatrix},$$

$$x = \begin{bmatrix} x^1 \\ x^2 \\ \vdots \\ x^p \end{bmatrix}, \text{and } d = \begin{bmatrix} f^r \\ f^2 \\ \vdots \\ f^p \end{bmatrix}$$

The MRIO can then be expressed as:
x – a vector of gross output for each of the p regions
A^{rr} a regional technical coefficient matrix intra-spatial unit $A^{rr}=\begin{bmatrix} a_{11}^{rr} & \cdots & a_{1n}^{rr} \\ \vdots & \ddots & \vdots \\ a_{n1}^{rr} & \cdots & a_{nn}^{rr} \end{bmatrix}$
A^{rs} a technical coefficient matrix inter-spatial unit between unit r and s $A^{rs}=\begin{bmatrix} a_{11}^{rs} & \cdots & a_{1n}^{rs} \\ \vdots & \ddots & \vdots \\ a_{n1}^{rs} & \cdots & a_{nn}^{rs} \end{bmatrix}$
I the Identity matrix (“1” in the diagonal, “0” in all other fields)
$(I\text{-}A)^{-1}$ an inverse of a square matrix (also known as the Leontief inverse). A sector’s output can be broken down in output required to meet final demand and output used by other sectors (intermediate demand). The Leontief inverse matrix allows the estimation of individual sectoral output multipliers capturing the direct and indirect economic effects of exogenous shifts in final demand.

An induced or Type II multiplier incorporates the impact of household spending in addition to the direct and indirect impact. Augmenting the Leontief Inverse Matrix with wage income per unit output[3] w and FC_r is the total final consumption of households[4], we produce the Augmented Leontief Inverse Matrix:

$$(I_a\text{-}A_a)^{-1}$$

The input-output model can be extended to account for environmental emissions associated with production activities by multiplying the economic output of a sector at each stage (vector x as shown earlier) by the diagonal matrix of sectorial environmental burden coefficients (e.g. GHG emissions per monetary or physical unit of output) B

$$e_k = B_k(I - A)^{-1}d$$

where e is the total (direct and indirect) environmental impacts vector per unit of final demand (Tsakiridis *et al.*, 2020). The subscript k denotes the type of environmental impact, while matrix B_k has diagonal elements representing the environmental impacts of interest per unit of output for each process (Hendrickson *et al.*, 1998). This process relates GHG emissions, in this case methane, to economic output so demonstrates how big a fall in beef output is required to achieve a 10% reduction in methane. The extent to which the exogenous shock of the herd reduction spreads through the rest of the economy is indicated through the use of multiplier effects.

The sub-regional model, based on work by O’Donoghue (2021), provides multipliers for three regions: Limerick city, the Mid-West NUTS 3 region, and the rest of the country. The Mid-West region in the is model is comprised of the rest of Co. Limerick, Co. Clare, and Co. Tipperary. Therefore, the sub-regional IO model can provide economic multipliers related to changes in economic activity at a level quite close to the county level examined in this paper. The data used for the sub-regional IO model is further described in the Annex.

4. DATA

The survey used for this study was undertaken in Co. Clare, in the west of Ireland. Clare was chosen as the

[3] Including Operating Surplus for sectors with high numbers of sole traders, such as agriculture, construction, transport etc.
[4] The consumption rate per € of wage is defined as $c_{r,i}=FC_{r,i}/W_r$.

Table 1. Comparison of farming in Clare and Ireland.

	Clare	National
Population	118,817	4,761,865
Daytime working population	34,761	2,304,037
People in agriculture, forestry, and fishing	3,423	89,116
Number of Farms	6,297	135,037
Specialist Beef Farms	5,109	74,159

Source: Census of Agriculture 2020 and Census of Population 2016.

study area for this paper for two specific reasons. Firstly, nearly 10% of the working population in the county are employed in agriculture, forestry, and fishing (see Table 1). This is substantially higher than the number employed in agriculture for the entire country, which is just under 4%.

Secondly, Table 1 shows that, of the 6,297 farms located in Co. Clare, over 81% of them are beef specialists. Again, this value is much higher than the national average, which is 55%. Hence, cattle farming is a relatively important source of employment in Clare. In this paper, we hypothesise that cattle farmers' earnings feed into the wider Clare community, thus meeting one of the primary goals of the CAP's Rural Development Plan: rural viability. We then estimate how changes to the local beef sector in Clare would hypothetically influence rural viability in the county.

While the SMILE-FARM model provides the spatial distribution of farms with their incomes, costs, and technical attributes, we also need to collect data in relation to the location of purchases and sales by type of good. This data provided us with the necessary information about the source location for inputs and the output destination for cattle outputs among cattle farmers in the county. The resulting sample of Clare farms was matched with the SMILE-FARM model so that spatial analysis could be carried out with reference to the activities of all cattle farms in the county. A more detailed description of the data sources used for this paper and the methodology used to collect the data from Clare farmers is available in the Annex.

5. RESULTS

Outputs from the SMILE Model – Spatial distribution of agriculture in County Clare

The census data indicate the importance of specialist beef production to farming in Clare with some variability within the county in terms of the reliance upon specialist beef production. In Figure 1, we show the share of farmers engaged in specialist beef production. The results indicate some variability between the north and south of the county. Farming in many parts of the north is almost exclusively dependent on specialist beef production. Many parts of the south have a relatively high share of farmers devoted to other activities such as dairying or mixed livestock grazing. This explains why the share engaged in specialist beef production is below 63 per cent in parts of the south.

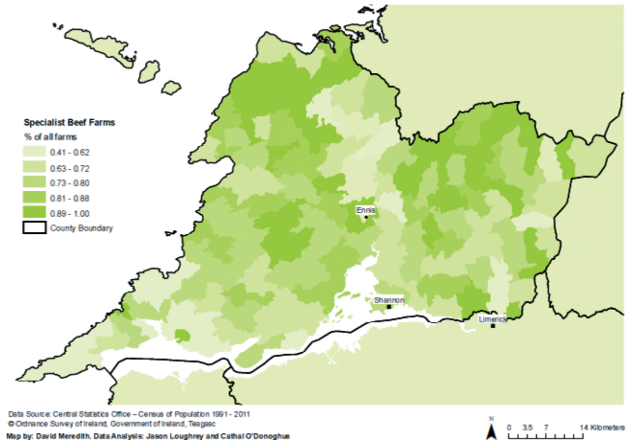

Figure 1. The share of farmers classified as specialist beef producers in Clare.

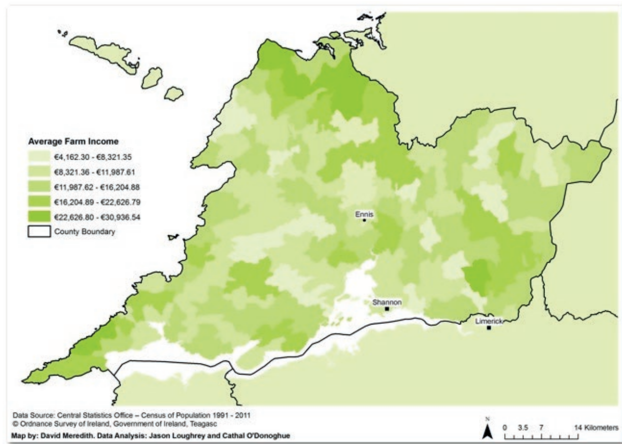

Figure 2. Spatial distribution of family farm income in 2006.

In Figure 2, we present the spatial distribution of family farm income using five income brackets. The definition of family farm income includes agricultural subsidies but excludes off-farm income. Figure 2 indicates that farm income is highest in the very north of the county. The relatively high farm income in this area may be attributed to the higher than average farm size. The

Table 2. Share of cattle farm output sold in Co. Clare regions according to geographical point of sale.

Region	Outside	North-west	South-west	North-east	South-east	Ennis
North-west	71.5	12.7	3.4	0.6	1.5	10.4
South-west	57.5	12.0	13.5	0.1	2.9	14.1
North-east	73.7	0.1	0.0	15.6	4.0	6.6
South-east	79.7	0.3	0.1	4.4	9.2	6.3
Ennis	83.5	1.6	0.0	0.0	7.2	7.6
Total	72.0	6.9	4.0	3.7	4.3	9.2

relatively lower income in the south emerges despite the fact that dairy farms have higher incomes than specialist beef producers and dairy farms are more common in the south. The patterns suggest that there are many low-income specialist beef producers in the south and north-east of the county. These farm households are economically vulnerable unless decent off-farm employment is available.

Cattle farmer income and expenditure in County Clare

In this section, we present results regarding the flows of cattle farming inputs and outputs in the county as facilitated by the matching of the Clare survey data to the SMILE model. For analytical purposes, we provide these results according to six regions i.e. North-West Clare, South-West Clare, North-East Clare, South-East Clare, Ennis and outside Clare. The four within-Clare regions are defined roughly according to their position relative to the town of Ennis. As Figures 1 and 2 show, the majority of the geographical area in the county is west of Ennis town. It is therefore unsurprising to find that the majority of farmers and agricultural output comes from that part of the county.

In Table 2, we provide the share of output[5] for each of the six regions based on the geographical point of sale. This includes the share of output sold to outside the county. Table 2 shows that 72% of beef cattle farm output goes outside of the county. This high figure is primarily driven by how beef cattle farming in structured in Clare and the rest of the country. Cattle farming in Clare is dominated by suckler farming, where calves from suckler cows are reared for six to nine months until weaning takes place and the calf is sold to another farm for further finishing (Teagasc, 2015). These finishing farms are located mainly outside Clare, principally in the east of Ireland. The remaining output goes to the west of the county (10.9%), the east (9%) and Ennis town (9.2%), with the majority of output not going outside the county staying within each region.

Inputs and overheads

We have now established some important findings about the point of sale for livestock sales. In Table 3, we present the share of direct inputs and overheads purchased from each of the six regions. Direct inputs include feed, machinery hire, casual labour and fertiliser. Overheads include electricity, telephone costs, interest payments and depreciation of assets. We find that almost 9% of expenditures are sourced from Ennis town and 10.5% from outside the county. Among specialist beef farms, we find that just over half of all overheads and inputs are sourced from the west of the county. Approximately 29.5% are sourced from the east of the county.

Table 3 also shows that for all regions except Ennis, the majority of inputs are purchased within the same regional area. This is particularly the case in the western part of the county, where over 60 per cent of inputs are purchased locally. The findings have much in common with those of Pritchard *et al.* (2012) where there is clear evidence that farm households and businesses make extensive use of their local towns for maintenance purchases and a range of other supplies. Pritchard *et al.* (2012) label this tendency to buy local as the 'local if possible principle'.

Overall, the findings suggest that a change in the volume and value of the cattle herd in Clare will lead to output changes for those companies supplying the specialist beef farmers with inputs. The information supplied in Table 3 suggests that nearly 90% of these output changes would come from within the county. The multiplier effects at the county level are therefore likely to be more important than in the case of most other industries.

[5] In this context, by output we mean the monetary value of production.

Table 3. Share of cattle farm inputs coming from Co. Clare regions.

Region	Outside	North-west	South-west	North-east	South-east	Ennis
North-west	13.4	60.7	11.1	3.1	3.5	8.2
South-west	4.6	13.7	68.9	0.9	4.0	7.8
North-east	9.6	7.0	2.6	53.1	18.7	9.0
South-east	10.8	5.8	2.8	18.6	53.2	8.8
Ennis	10.5	25.2	7.7	4.7	15.1	36.8
Total	10.5	25.8	25.4	12.3	17.2	8.8

Effects of changes in the beef industry to the environment and local economy

In this section, we present results regarding the overall effect for the wider Clare economy of a hypothetical decline in the size of the cattle herd in the county. The Food Vision 2030 policy document was published by the Irish government in 2021, providing a roadmap for the Irish agri-food sector up to the year 2030 (DAFM, 2021). The document commits to a reduction of at least 10% in biogenic methane by 2030 (based on 2018 levels) in the agri-food sector in Ireland. We assess what the overall impact of a such a reduction would be in an area heavily dependent on cattle farming such as Co. Clare. It is assumed that the 10% reduction in methane is achieved entirely through a reduction in the beef cattle herd, with dairy cattle numbers continuing to increase at the current rate and sheep numbers staying constant. This is compared with a scenario where beef cattle number increases seen post-quota removal (2016-2018) are extrapolated at a decreasing rate to the year 2030 until a steady state is achieved. There are two main reasons for concentrating of a reduction in the beef cattle herd. First, beef has the highest GHG footprint per euro of output of all the major sources of protein produced in Ireland (Tsakiridis *et al*. 2021). Second, the other main source of agricultural methane emissions (dairy) is currently far more profitable at the farm level than beef farming (Dillon *et al*., 2021).

The environmental impact of a 10% reduction by 2030 in methane in Co. Clare is shown in Table 4. An overall 10% reduction in the beef cattle herd is unequally distributed across the county. In order to achieve a 10% county wide reduction, reductions of 16.3% in the north-west, 13.5% in the south-west and 11.7% in the south-east are necessary. This compares with lower levels of methane reduction in the north-east and Ennis regions. Table 4 also shows that reducing methane emissions through reduction in the beef cattle herd also reduce the production of organic nitrogen with the highest percentage nitrogen reductions being achieved in the west of the county.

Table 4. Percentage change in emissions in the Clare Regions with a 10% cut in methane emissions in cattle production.

Region	Methane	Greenhouse Gases	Organic N
Clare	-9.8	-9.7	-11.9
North-west	-16.3	-16.2	-18.6
South-west	-13.5	-13.4	-15.7
North-east	-5.4	-5.3	-7.2
South-east	-11.7	-11.6	-13.9
Ennis	-9.5	-9.4	-11.4
National	-4.6	-4.4	-6.4

In Figure 3, the relative economic impact of reducing methane by 10% is observed. The reduction in the beef cattle herd causes an 18.6% fall in output from that sector by 2030, relative to 2018. As the dairy herd continues to increase in size, a 27.8% increase in dairy output is observed. The sheep herd remains constant so only a 0.008% drop in economic output is seen from 2018 to 2030. Although there is a larger percentage increase in dairy output than there is a drop in beef cattle output, the much larger size of the beef herd means that overall economic output over the time period remains almost flat, with a 0.01% fall in output being observed.

The wider economic effects of the 10% reduction in methane can be seen in Table 5. The reduction in the beef cattle herd results in a €9.34 million decrease in total output in 2030 relative to a scenario where cattle numbers continue to increase at the current rate. The reduction in output is concentrated in the Mid-West region of which Clare is part with €8.59 million of the reduction taking place there. The indirect multiplier is 0.68, indicating that there is an additional €680,000 loss to the Irish economy for every €1 million reduction in spending by beef cattle farmers in Clare. The majority of indirect spending takes place in the Mid-West region but more of the multiplier effect is felt out-

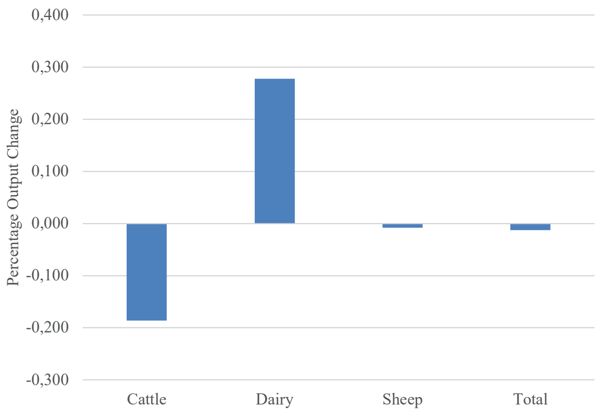

Figure 3. Percentage change in output in County Clare for a 10% reduction in methane.

side the region than for the direct multiplier with 37% of spending taking place outside the Mid-West region. The induced multiplier which takes employee spending effects into account is 0.29. The small size of the multiplier reflects the limited amount of employment provided by agriculture compared to other industries. Again, a large proportion of the multiplier (78%) is located within the Mid-West region. When direct, indirect and induced effects are taken together, there is an €18.4 million reduction in economic activity in 2030 following the decrease in the beef cattle herd with €14.72 million of that reduction taking place within the Mid-West region.

Following on from the effects of a reduction in methane emissions on the wider economy, the effects of the methane reduction at the farm level can be seen in Table 6. Teagasc, the Irish agricultural advisory service, defines a farm business as being economically viable if family farm income (FFI) is sufficient to remunerate family labour at the minimum wage and provide a five per cent return on the capital invested in non-land assets, i.e. machinery and livestock. Table 6 shows the percentage of beef cattle farms that are considered viable with and without the 10% reduction in methane emissions. There are 9% fewer viable beef cattle farms in Co. Clare following the methane reduction, with the largest falls in the number of viable farms taking place in the north-west, the north-east and Ennis. The viability gap measures how far the average farm is from the viability threshold. The imposition of a reduction in methane emissions would put the average beef cattle farm 60% below the viability threshold, compared with 52% with the emissions reduction taking place. Farms in the north-west of the county would suffer the biggest viability gap increase, moving a further 16% away from the viability threshold.

Table 5. Economic effects of beef industry changes after a 10% reduction in methane.

Region	Direct	Indirect	Induced	Total
Rest of country	-0.37	-1.66	-0.39	-2.42
Mid-West	-8.59	-4.02	-2.11	-14.72
Limerick	-0.38	-0.67	-0.20	-1.25
Total	-9.34	-6.35	-2.71	-18.40
Multipliers				
Rest of country	0.039	0.178	0.042	0.259
Mid-West	0.920	0.431	0.226	1.577
Limerick	0.041	0.071	0.022	0.134
Total	1.00	0.68	0.29	1.970

Table 6. Changes in beef cattle farm viability with 10% methane reduction.

	Viability Rate			Viability Gap		
Region	Baseline	Methane Cut	Change	Baseline	Methane Cut	Change
North-west	0.27	0.24	-11%	0.45	0.52	16%
South-west	0.29	0.27	-5%	0.49	0.56	14%
North-east	0.28	0.25	-11%	0.47	0.52	9%
South-east	0.31	0.29	-9%	0.50	0.56	13%
Ennis	0.26	0.23	-12%	0.46	0.51	12%
Total	0.29	0.26	-9%	0.52	0.60	13%

6. DISCUSSION AND CONCLUSIONS

In this paper, we have examined the importance of the beef cattle sector to the local economy of Co. Clare in Ireland and the potential impact of GHG mitigation measures in this sector upon wider economic activity. Our findings suggest that Irish beef cattle farmers are inclined to purchase most of their inputs from within their own immediate area, thus indicating that the 'local if possible principle' is followed by many farmers in the county. The findings suggest that a substantial share of livestock sales tend to take place in the main county town of Ennis and thus away from the immediate hinterland of many cattle farmers. This shows that farmers will travel longer distances for specific transactions, but the overall results indicate that small towns and villages are deeply connected with the agricultural hinterlands. As in the case of Pritchard *et al.* (2012), the analysis suggests that a viable local farming sector supports local towns and the basic commercial functions demanded by farm households.

The empirical analysis has further examined the impact of a reduction in the size of the herd in Co. Clare to meet GHG emission targets. The overall impact of such a decline is capable of reducing total primary cattle output by €9.3 million, with €8.6 million of the reduction located within the Mid-West region. When multiplier effects are included, the overall decline in economic output is €14.7 million in the Mid-West region and €18.4 million overall. The number of beef cattle farms in Co. Clare considered viable is also reduced by 9% as a result of the mitigation measures. Overall direct economic output within the agricultural sector in Co. Clare remains almost unchanged due to increases in dairy output that offsets the beef output reduction.

The results are in line with other analyses such as Wu *et al.* (2015) and Bourne *et al.* (2012) that show that the implementation of GHG mitigation measures in agriculture can lead to a reduction in output from the agricultural sector, in this case beef. When multiplier effects are included, the overall economic loss is almost double the direct loss, showing how strongly linked the beef sector is to the local economy.

This analysis shows that the distributional and spatial impact of mitigation measures must be taken into account when designing policy instruments. Given the high global warming potential (GWP) associated with methane, ruminant animal agricultural systems are highly likely to be subject to increasing emissions mitigation measures in the coming years. With the wide disparity between Irish beef cattle and dairy farm incomes, as well as value added opportunities, it is likely that methane reductions will be concentrated on the beef sector. As a result, policymakers must prepare mechanisms to offset the costs incurred by those most affected by these measures.

The results of the multiplier analysis show that the beef sector is highly embedded within the regional economy with indirect and induced effects almost doubling the direct impact of the cattle herd reduction. Localised value chains are also observed in other regions of Europe where beef cattle farming is prominent (Vázquez-González *et al.*, 2021; Pays de la Loire Regional Council, 2019). GHG mitigation measures that impact upon cattle farming will affect not just the farmers themselves, but a chain of businesses and households connected to the beef value chain. In an environment where such policy measures are becoming more likely to be implemented, as well as shifting consumer demand away from meat products, governments will need to quantify the size of the impact on affected industries, as well as what steps should be taken to assist those affected.

Some attention has been paid to the idea of a 'just transition' for those most affected by climate change mitigation measures, in order to support communities transitioning to a low carbon economy (Blattner, 2020; Heyen *et al.*, 2020). As part of the European Green Deal, a Just Transition Mechanism (JSM) worth €55 billion over six years exists to alleviate the socioeconomic impact of the transition to a low carbon economy. Investments such as these will be required to offset losses arising from GHG mitigation measures, especially in areas where alternative sources of employment are scarce. Such a possibility is put forward by Hynes *et al.* (2009b) who use spatial microsimulation to model an agricultural methane tax in Ireland with revenue raised being redistributed in the form of an environmental subsidy to farmers. The study found that such a measure would encourage farmers to participate in the scheme and could also have the effect of moving low income farms up the earnings distribution ladder.

Efforts to meet GHG emission targets are not the only potential reason for a decline in the cattle herd. Beef cattle farming continues to be loss-making on average, with an increasing age profile, and greater competition for farmland. Regardless of the cause for the decline in the cattle herd, the multiplier effects remain important. The potential losses to farm income further underline the importance of off-farm employment as an alternative income source.

The effect of a reduction in beef cattle farming is also complicated by the nature of agricultural land in Co. Clare, 94% of which is classed as severely disadvantaged, and thus unsuitable for the intensive production seen in dairy farming. Alternative approaches to agriculture have proven successful in the region with agri-environment schemes such as the Burren Farming for Conservation Programme (BFCP) and Burren Programme (BP) proving successful in the Burren region, which covers an estimated 72,000 ha of land in Counties Clare and Galway (Dunford & Parr, 2020). These programmes utilise a 'hybrid' approach whereby farmers are rewarded annually for their environmental performance while also having access to a fund to carry out self-nominated 'conservation support actions' to help improve conservation performance over time.

In addition, the Basic Payment Scheme, environmental and the rural development payments play an important role in sustaining these farming communities. Given the increasing environmental orientation of EU policy, future agricultural payments to farmers should take account of the role of farmers in environmental stewardship and as economic pillars of local communities (McGurk *et al.*, 2020; Rizov *et al.*, 2018). Conversion to organic beef farming may also be an option for some farmers as required inputs are very similar to non-organic beef farming and incentive schemes already exist to support the sector (O'Donoghue *et al.*, 2018). Additionally, organic farms tend to localise in places like Co. Clare, far from more competitive agriculture, characterised by a high specialization in arable crops and a more intensive use of mechanisation and chemicals (Bonfiglio & Arzeni, 2019). While this paper has emphasised the local economic impact of beef cattle farming, it should be acknowledged that beef production has a strong export orientation and that a wider treatment of the contribution of beef cattle farming to the overall economy should reach beyond a local/global dualism.

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THE LOCAL ECONOMIC IMPACT OF CLIMATE CHANGE MITIGATION IN AGRICULTURE - ANNEX

Sub-regional IO model data

The sub-regional IO model uses census-derived, commuting flow employment data at a sub-county or district scale to downscale regional and national input-output data. The national IO table containing 58 industrial sectors is collapsed to an 8-sector[6] model for which localised employment data derived from the most recent 2016 census exist. Spatial interaction models of the inputs and outputs in different sectors in different areas are estimated as a function of the distance to different markets and the characteristics of these markets using information from an industry survey.

Data collection

To facilitate data collection, an application was made to undertake a series of queries on the Teagasc Client Information Management System (CIMS). This request was granted subject to a number of conditions associated with ensuring the confidentiality of the data. A number of queries were run to (i) identify all Teagasc clients in Co. Clare; (ii) identify all Teagasc clients with a beef enterprise from this subset of data; and (iii) identify those enterprises where beef production was the primary type of farming undertaken on the farm.

Using spatial analytical techniques, Co. Clare was divided into four sub-regions by applying a horizontal and vertical transept that bisected Ennis. (i.e. Clare was divided into four sub-regions with Ennis at the centre). Each of the farms selected from the CIMS was allocat-

[6] These 8 sectors are food and agriculture; manufacturing and industry; building and construction; commerce; training, storage and communications; public administration and defence; education, health and social work; and other.

ed a sub-region identification number based on their address. These data were incorporated into a statistical analysis package and a random sample of 100 farms was identified from each sub-region.

The survey was carried out by contacting the selected farmers by telephone. If a farmer did not wish to participate in the survey, the next farmer on the list was contacted until 13 farms in each of the sub-regions had been surveyed. This resulted in a sample of 52 farms being surveyed.

Once complete, the survey data were entered into a spreadsheet and the data restructured to extract four individual survey sections. These included (i) the address of the farm; (ii) the structure of the farm enterprise; (iii) the source (address) of inputs to the farm; and (iv) the destination (address) of outputs. All sections that incorporated address data were geocoded to facilitate spatial analysis (location allocation) within the SMILE model.

The survey data were then matched to the SMILE model using a statistical matching process known as the distance method. This method of matching from the survey to the SMILE model involves a set of overlapping variables that are common to both the survey data and the SMILE model. These variables included the farm type (i.e. dairy, specialist beef, crops etc.), demographic variables such as age and marital status, and economic variables such as the amount of direct payments. This allows the matching of farms of similar type from the farm survey data to the SMILE model and therefore achieve the necessary scale for spatial analysis.

The most basic implementation of the distance method uses distance functions with finite weights for the overlapping variables (Decoster *et al.*, 2020). To be precise, for a given record in the survey, the distance in the (selected) overlapping variables to every record in SMILE model is calculated. This could for instance be the difference in age, the difference in farm type, the difference in direct payments, etc. Then the weighted sum of these differences is calculated and finally the record in SMILE which has the smallest weighted sum is picked out. If there are several records which result in the same minimum distance, one of these records is chosen at random.

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Dealing with endogeneity in risk analysis within the stochastic frontier approach in agricultural economics: A scoping review

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Abstract. Literature on farm productivity and efficiency was reviewed using a scoping review methodology, focusing on studies that have included risk and risk management tools within the stochastic frontier analysis in agricultural economics. This study contributes to investigating the methods used to account for endogeneity by using a risk-accommodating stochastic frontier approach when analysing farmers' performance. Despite the increasing methodologies proposed in the literature, only a few studies have treated endogeneity in farm risk-performance evaluations. According to our findings, it can be concluded that there is a literature gap regarding the adoption of a comprehensive approach capable of dealing with endogeneity when assessing farm performances. Endogeneity and risk issues need to be concurrently addressed to make strides in achieving economic and environmental sustainability. Neglecting endogeneity in these analyses may lead to biased estimates and thus inappropriate policy recommendations failing to boost the productivity and technical efficiency of farmers.

Keywords: stochastic frontier analysis, agricultural economics, risk, endogeneity.
JEL codes: C18, Q12, D81.

HIGHLIGHTS

- Scoping review of studies that account for risk in Stochastic Frontier Analysis
- We synthesise methodologies dealing with endogeneity in risk-accommodating SFA
- The lack of risk and endogeneity accommodation in analysis yields biased results
- Literature gap in SFA dealing with risk and endogeneity in agricultural economics
- Risk and endogeneity inclusion may help develop effective agricultural policies

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1. INTRODUCTION

Agriculture is one of the sectors where risk and uncertainty play a decisive role in production decision-making (Ahsan *et al.*, 1982; Moschini and Hennessy, 2001). It is well-known that since farmers make input use decisions before knowing the true state of nature, they choose the input allocation according to their subjective propensity to take a certain level of risk (Ramaswami, 1992; Cerroni, 2020). While exerting their typical actions, farmers do not aim only to maximize profits but also try to minimize the risk impact on income loss (Just and Pope, 1978, 1979; Antle, 1983; Finger, 2013). The conceptualization of agricultural risk is usually attributed to the length and complexity of the biological production cycle, which exposes farmers to risks such as pests, erratic climatic changes, price fluctuations, and even policy changes (Duong *et al.*, 2019; Komarek *et al.*, 2020). According to Komarek *et al.* (2020), agricultural risks are classified into production, market, institutional, personal, and financial risks. Production risks stem from the natural growth processes and are also related to weather and climatic conditions. These are factors beyond the farmer's control given the stochastic nature of agriculture. Within market risks, there are those associated with price volatility for both input and output prices, as well as those related to asymmetric information, international trade, and liberalization processes. Institutional risks are generally associated with abrupt policy and regulation changes, as well as changes in the behaviour of informal institutions that affect transactions. Personal risks are farmer-specific and related to health, personal relationships, and well-being, whereas financial risks stem from farm finance factors, credit access, and interest rate payments.

Researchers and policymakers have various reasons to be interested in how risk affects farmers' decision-making and their economic performances. Farm performance evaluations are fundamental for policymakers and producers to enhance both the economic and environmental sustainability of farming (Farrell, 1957). Moreover, understanding the interrelations between farmers' behaviour in a risky environment and farm performance is essential to enhance the effectiveness of policy measures (Khanal *et al.*, 2021). For example, while risk-neutral farmers aim to maximize profits by considering only the mean effect of production, risk-averse producers account for both mean and higher moments of their production functions (Antle, 1983). Therefore, risk-averse production decisions differ from risk-neutral ones due to the marginal risk premium, which is the absolute value of the risk effect of input use on output (MacMinn and Holtmann, 1983; Ramaswami, 1992). The marginal risk premium may have a positive or negative sign and indicates whether risk-averse producers use more or less input than risk-neutral ones. Thus, risk-averse farmers use less risk-increasing (and more risk-decreasing) inputs to cope with risk compared to a risk-neutral farmer, who employ the profit-maximizing input vector (Nelson and Loehman, 1987; Ramaswami, 1993). As such, the risk aversion due to the uncertainty of outcomes may result in non-profit-maximizing input use, potentially resulting in lower technical efficiency and productivity (Roll, 2019). By ignoring the risk impact on production, Battese *et al.* (1997) conclude that estimates of technical efficiency would be skewed. Consequently, neglecting the interrelation between farm performance and risk-averse deviations from efficient behaviour would lead to incorrect policy implications and recommendations (Just, 2003).

In literature, most productivity and efficiency analyses are conducted through the development of production frontier models. The two commonly used methods in productivity and efficiency analysis are Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA). Although these two methods have their merits, there has been constant debate amongst scholars on which method is better for modelling production technology. A relevant distinction between the two methods is that DEA is deterministic while SFA is stochastic. While in the stochastic frontier model, the individual observations may be affected by random noise, in the deterministic approach the potential noise is neglected, and each variation in data is assumed to influence the firm's efficiency and the shape of the frontier (Bogetoft and Otto, 2010). Therefore, one of the principal limitations of the DEA methodology is that it is not possible to consider the effect of risk on efficiency, which could be confused and interpreted as technical inefficiency. Accordingly, it seems that SFA might be more suitable to model productivity and efficiency in the presence of risk as it is suited to disentangle the inefficiency from the standard statistical error related, for example, to weather events, market volatility, and regulation changes.

Stochastic production functions appeared to be a reasonable solution to account for risk in agricultural economics (Chavas *et al.*, 2010). Just and Pope (1978) introduced a production function specification that can distinguish between the marginal effect of inputs on both the mean and variance of output. Then, Antle (1983) expanded this technique to account for the impact of production inputs on higher moments of production function (i.e., skewness). Later, Battese *et al.* (1997) extended the model proposed by Just and Pope (1978) to the stochastic frontier production approach developed originally by Aigner *et al.* (1977) and Meeusen and van Den Broeck (1977). According to the authors, the stochastic frontier production function is more consistent with economic theory and reality with regard to the so-called average production function. More recently, Kumbhakar (2002) generalized the approach proposed by the previous authors by estimating a model which includes production risk, technical efficiency, and producers' attitude toward risk. Given the inevitable consequence of risk effects on producers' technical efficiency, risk sources have to be incorporated into the stochastic production frontier to realistically account for and predict producers' technical efficiency (Battese *et al.*, 1997).

The primary motivation paving the way for the present study is that, despite its importance, most of the scientific literature on production at the farm level does not account for risk (Just, 2003). Moreover, it is worth mentioning that one of the central assumptions of the SFA model is that the input variables should be independent of both the error terms (technical efficiency and random error) in the model. It is the general definition of endogeneity, which refers to the correlation between explanatory variables and the error terms. However, it is essential to note that endogeneity may occur for several reasons. For instance, farmers may adjust their inputs according to observed shocks, which usually are included in the random error term. Therefore, the correlation between the production inputs and the statistical error term due to the observed shocks would result in endogeneity (Latruffe *et al.*, 2017). In addition, a possible endogeneity issue may arise when farmers, being aware they are inefficient, tend to optimize their input use (Shee and Stefanou, 2014). Finally, other endogeneity sources may occur when farmers cope with risk by adopting risk management tools or risk-mitigation practices (Vigani and Kathage, 2019). The model misspecifications due to the presence of endogeneity leads to erroneous inferences about the assessment of input elasticities and economies of scale, as well as inaccurate and inconsistent estimates of farm technical efficiency (Karakaplan and Kutlu, 2017). It is worth noting that endogeneity in SFA is often ignored, which could overstate or even undermine the effects of factors on production and, thus, results in key strategies or recommendations that boost farm performance being left out (Russo *et al.*, 2022). The impact of the inaccuracy and inconsistency of results may be highly relevant when risk analysis is performed (Battese *et al.*, 1997).

Given the motivations listed above, this paper presents a review of literature that covers agricultural productivity and efficiency analysis. The particular focus is on studies that have adopted the SFA method with the inclusion of risk. The scoping review method has been adopted for the capability to identify and map out evidence and clarify key concepts in agricultural stochastic frontier literature with the inclusion and consideration of risk. Specifically, this article aims to provide insights into how risks and risk mitigation strategies have been factored into SFA. The main contribution of the present research relates to analysing the different methods used to deal with endogeneity while aiming to investigate the risk effects on agricultural production within the SFA approach. It is important to highlight these two issues as when they are not considered in modelling, the biased estimates found after analysis may be used to inform policy. This then leaves room for the ineffectiveness of policy interventions as they would be developed without considerations of the complexity of the agricultural production modelling. The exclusion of the effects of risk and risk-mitigation practices on studies that aim to investigate farmers' decision-making would provide inconsistent and irrelevant production guidelines. This review depicts the gaps that researchers need to fill and methods that can be adopted to ensure valid and consistent results that can be used for policy development aimed at ensuring agricultural productivity and efficiency.

In the following section, the scoping review methodology, eligibility criteria, and selection process of articles are presented. The results section, presents and illustrates insights of the literature analysed. Finally, we discuss the results and provide some conclusions, highlighting the limitations of the study and future research areas.

2. METHODOLOGY

The scoping review method was adopted to conduct the study following the guidelines provided by Tricco *et al.* (2018) in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR). A scoping review is a form of knowledge synthesis that systematically searches, selects, and synthesizes existing knowledge to map the key concepts, types of evidence, and gaps in research related to a given area or field (Colquhoun *et al.*, 2014).

The advantage of the scoping review method is that it helps to summarise the existing knowledge used to develop policy or practical recommendations, as well as to provide practical pathways for future research (Arksey and O'Malley, 2005; Piñeiro *et al.*, 2020). Compared to the traditional literature review, the scoping method is more rigorous, transparent, and replicable, including steps to reduce the subjectivity bias resulting from the author's prior knowledge and experience (Munn *et al.*, 2018). The scoping method was thus suitable for this study in exploring how risk has been incorporated into SFA agricultural productivity analysis and how the endogeneity issues have been handled in literature.

After stating the research question, the subsequent steps of this approach are the identification of relevant studies, study selection, data extraction and charting, and reporting of the results. In order to get a representative sample of the literature, an initial set of articles was identified. The Scopus bibliographic database was used to research the relevant studies, including articles written in English and published in peer-reviewed journals earlier than 30 June 2021. We opted to focus on articles indexed in Scopus since it is one of the two most used bibliographic databases, and it includes most (about 99%) of the journals indexed in Web of Science (Singh *et al.*, 2021), particularly in the social sciences topics (Mongeon and Paul-Hus, 2016).

The search was characterized by a combination of three keyword groups included in the paper abstract, title, or keywords. The following structured query developed using Boolean operators and wildcards was used for the research:

["stochastic frontier" OR "stochastic production" OR "technical efficiency"] AND ["risk" OR "uncertain"] AND ["farm*" OR "agricultur*" OR "food" OR "crop" OR "livestock"].*

While the first set of keywords included the terms related to the SFA, the second related to the risk, and the third to the agricultural context.

The final set of articles was exported to the Mendeley referencing tool for assessment. For consistency purposes, all the authors screened the initial set of articles. We screened the same publications and discussed our chosen studies for review. To be included in the sample, the eligibility criteria used the following: (i) research topic on agricultural production (ii) inclusion of risk and risk management in farm productivity and efficiency analysis; (iii) the adoption of SFA to model technical efficiency and agricultural productivity.

The selection process followed several steps which gradually reduced the number of studies according to the eligibility criteria, as shown in Figure 1. The search output initially included 162 peer-reviewed articles. In the first screening step, titles and abstracts were examined, where papers focusing on issues related to risk analysis in the agricultural sector using the SFA approach were retained. Then, the full text of the remaining 94 studies were analysed, excluding 35 articles according to the rejection criteria. Finally, in the last screening step, 15 papers were excluded because they utilized a stochastic production function instead of the frontier. However, these papers were examined to consider their insights as regarding endogeneity issues. At the end of the screening process, 44 articles were retained. Of the 162 articles, 11 were disqualified because they were not focused on agricultural economics, and 40 for the lack of risk considerations. Finally, 67 papers were excluded for their use of methods other than SFA, for instance, stochastic production function (e.g., Griffiths, 1986; Eggert and Tveteras, 2004; Di Falco *et al.*, 2007), or non-parametric approaches such as DEA (e.g., Serra and Oude Lansink, 2014; Chambers *et al.*, 2015; Oude Lansink *et al.*, 2015), or fuzzy mathematical models (Guo *et al.*, 2019; Wang *et al.*, 2020).

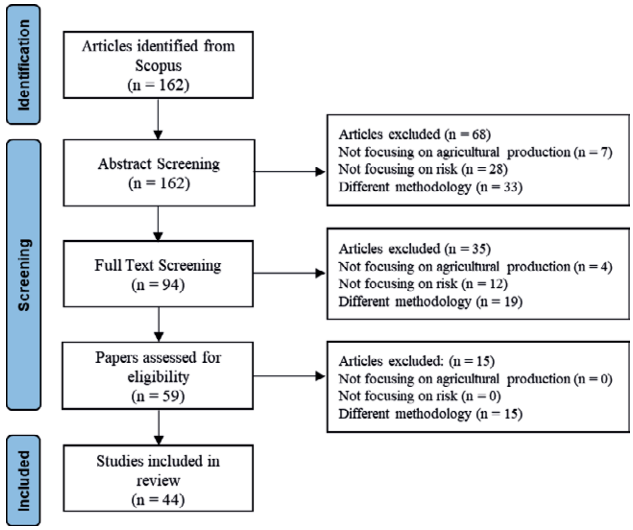

Figure 1. PRISMA-ScR Flow diagram. Source: Own elaboration based on Tricco *et al.* (2018).

3. RESULTS

The results of the analysis showed that there are several approaches adopted in estimating stochastic production frontiers with risk considerations. Figure 2 below presents a histogram of the distribution of the common approaches employed in the retained articles. The most commonly used methods were those of Just and Pope (1978), Battese and Coelli (1995), Battese *et al.* (1997), and Kumbhakar (2002). In addition, 15 articles adopted other methods that studied risk in their analysis[1].

[1] Among them, there are the approaches proposed by Aigner *et al.* (1977), Antle (1983), Blarel *et al.* (1992), Caudill *et al.* (1995), Koop

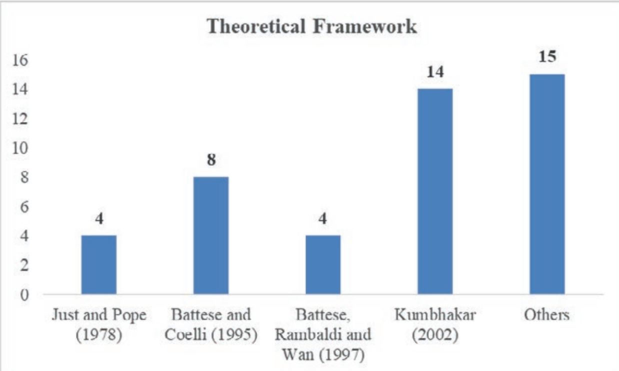

Figure 2. Theoretical and methodological framework to estimate the production frontier. Source: Own elaboration. Note: The sum is 45 because one article compared the Just and Pope and Kumbhakar models.

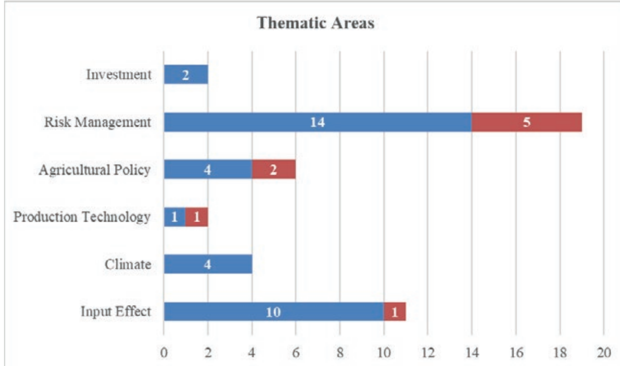

Figure 3. Literature thematic areas accounting for the articles that dealt with endogeneity issues. Source: Own elaboration.

However, not all approaches allow the inclusion of risk within the stochastic production framework, such as Battese and Coelli (1995). Among the techniques that include risk within the production frontier, the most common methods used were the ones proposed by Just and Pope (1978), Battese *et al.* (1997), and Kumbhakar (2002)[2].

Six different thematic groups were identified within the literature analysed, as shown in Figure 3. In this analysis, it was found that two articles incorporated risk in the SFA approach by focussing on the relationship between efficiency, risk aspects, and investment, such as the timing of investment decisions (Lambarraa *et al.*, 2016) or the adoption of new technology (Ghosh *et al.*, 1994). In addition, nineteen articles investigated the effect of farmer risk attitudes, risk mitigation practices, and risk management tools on farm performance. Furthermore, six papers examined the impact of agricultural policies on production risk and technical efficiency. Additionally, two studies investigated the differences in production risk and technical efficiency among distinct production technologies, such as intensive or extensive (Nguyen *et al.*, 2020) and organic or conventional production (Tiedemann and Latacz-Lohmann, 2013). In addition, four papers investigated the climate effect or market volatility on farm performance and/or risk. Finally, eleven articles focused on the assessment of the impact of input on production risk and technical efficiency. In Figure 3, the articles that dealt with endogeneity and those that did not are differentiated with colour schemes. The colour red represents the articles that dealt with endogeneity. As a result, only nine studies out of 44 (about 20%) considered the issue of endogeneity. Among them, five articles focused on the risk-management thematic area, two on agricultural policy, one on production technology, and one on input effects.

The different methods implemented to account for endogeneity are presented in Table 1. Among the articles in the risk management thematic area, Chang and Wen (2011) investigated the off-farm work effect on technical efficiency and production risk in Taiwan rice farming, Mishra *et al.* (2019, 2020) examined the impact of contract farming on production risk, technical efficiency, and risk attitudes for different crops in Nepal, and Rizwan *et al.* (2020) studied the effect of off-farm employment on production risk and technical efficiency. All these articles developed a stochastic frontier following the model proposed by Kumbhakar (2002), accounting for self-selection by separating adopters and non-adopters. Khanal *et al.* (2021) investigated the influence of farmers' climate change adaptations on smallholder farm efficiency and productivity in Nepal rice production. The authors treated the self-selection endogeneity bias among adopters and non-adopters for observed and unobserved characteristics. In particular, they utilized the Propensity Score Matching (PSM) technique to correct for observed heterogeneity, obtaining samples of farmers homogenous in terms of socioeconomic characteristics. Then, they estimated a stochastic frontier using the model proposed by Bravo-Ureta *et al.* (2012) to correct for unobserved heterogeneity.

In the agricultural policy thematic area, Key and Mcbride (2014) estimated the effects on production mean and variance caused by the ban of antibiotics on the US hog industry. They developed a stochastic fron-

et al. (1997), Greene (2003, 2005), Tsionas (2006), Yesuf *et al.* (2008), O'Donnell *et al.* (2010), Power *et al.* (2011), Bravo-Ureta *et al.* (2012), Karagiannis and Tzouvelekas (2012), Kumbhakar *et al.* (2014), and O'Donnell (2016).

[2] While all the studies consider risk, not all explicitly include it within the estimated production frontier. Some articles assessed it outside the model as a prerequisite or a follow-up step after the estimations.

tier following the approach proposed by Karagiannis and Tzouvelekas (2012). The authors addressed the potential selection bias as the application of antibiotics treatment may be related to other unobserved aspects influencing the production process. In particular, they matched the different treatment effects (antibiotics) to create similar groups based on the observable characteristics. Singbo *et al.* (2020) analysed the impact of the revenue insurance program and environmental regulations on Canadian hog farmers' behaviour and farm performance indicators. The authors addressed the potential endogeneity of input changes related to production shocks by estimating the meta-technology production frontier model developed by O'Donnell (2016).

Within the production technology thematic area, Tiedemann and Latacz-Lohmann (2013) evaluated production risk and technical efficiency in organic and conventional arable crop farms in Germany. The authors developed a stochastic frontier approach stemming from the model developed by Just and Pope (1978). They used the propensity score matching to compare groups, accounting for the self-selection problem due to farm size and soil quality.

Finally, among the input effects thematic area, the only study that dealt with endogeneity is Nauges *et al.* (2011), who analysed Finnish grain production under both inefficiency and risk conditions. They developed a state-contingent production frontier following the model proposed by O'Donnell and Griffiths (2006). They accounted for the endogeneity of inputs considering the different states of nature. In particular, they considered that farmers allocate inputs differently to manage risk in relation to the meteorological conditions in the relative states of nature.

To summarise, seven articles considered endogeneity bias resulting from self-selection, while two considered endogeneity stemming from input use alterations after adverse shocks.

In addition to results related to SFA, some other articles which emerged from the search string accounted for endogeneity in the production function. These papers are reported in Table 2. All these articles were classified into the risk-management thematic area.

Among these articles, Di Falco and Chavas (2009) analysed the crop genetic diversity effects on productivity and production risk of Ethiopian farmers engaged with barley production, following the Antle (1983) approach. The authors estimated the mean function, the variance, and the skewness equations using a three-stage least squares (3SLS) estimator to correct the self-selection bias, treating biodiversity as endogenous in all equations. Following the approach proposed by Antle (1983), Di Falco and Veronesi (2014) investigated the influence of climate change adaptations on farm exposure to downside risk for several crops in Ethiopia. The decision on whether to adapt or not to climate change is voluntary and may result in self-selection bias. The authors accounted for the endogeneity of the adaptation decision by estimating a switching regression model. By using the same approach, Kassie *et al.* (2015) analysed the effect of sustainable intensification practices on productivity and production risk in maize-legume intercropping production in Malawi, while Amondo *et al.* (2019) investigated the impact of using drought-tolerant

Table 1. Articles dealing with endogeneity in the production frontier estimates.

Category/Study	Frontier Theoretical Framework	Endogeneity Source	Methodology
Risk Management			
Chang and Wen (2011)	Kumbhakar (2002)	Self-Selection	Separating Groups
Mishra *et al.* (2019)	Kumbhakar (2002)	Self-Selection	Separating Groups
Mishra *et al.* (2020)	Kumbhakar (2002)	Self-Selection	Separating Groups
Rizwan *et al.* (2020)	Kumbhakar (2002)	Self-Selection	Separating Groups
Khanal *et al.* (2021)	Bravo-Ureta *et al.* (2012)	Self-Selection	PSM
Agricultural Policy			
Key and Mcbride (2014)	Karagiannis and Tzouvelekas (2012)	Self-Selection	PSM
Singbo *et al.* (2020)	O'Donnell (2016)	Input Endogeneity	Meta-Technology
Production Technology			
Tiedemann and Latacz-Lohmann (2013)	Just and Pope (1978)	Self-Selection	PSM
Input Effect			
Nauges *et al.* (2011)	O'Donnell and Griffiths (2006)	Input Endogeneity	State-Contingent

Source: Own elaboration.

Table 2. Articles dealing with endogeneity in the function production instead of the frontier.

Category/Study	Frontier Theoretical Framework	Endogeneity Source	Methodology
Risk Management			
Di Falco and Chavas (2009)	Antle (1983)	Self-Selection	Three-Stage Least Squares (3SLS) approach
Di Falco and Veronesi (2014)	Antle (1983)	Self-Selection	Endogenous Switching Regressor
Kassie *et al.* (2015)	Antle (1983)	Self-Selection	Endogenous Switching Regressor
Mallawaarachchi *et al.* (2017)	Quiggin and Chambers (2006)	Self-Selection Input Endogeneity	Two-Stage IV approach State-Contingent
Wang *et al.* (2018)	Antle (1983)	Self-Selection	Two-Stage IV approach
Amondo *et al.* (2019)	Antle (1983)	Self-Selection	Endogenous Switching Regressor

Source: Own elaboration.

maize varieties on farm productivity, yield variance, and downside risk exposure in Zambian maize-growing farms. The research proposed by Wang *et al.* (2018) studied the importance of irrigation infrastructure in enhancing farmers' ability to adapt to drought and its efficacy in managing drought risk in rice production in China. The authors estimated a production function following the approach proposed by Antle (1983). In addition, they implemented a two-stage instrumental variable method to control for the endogeneity of the adaptation decision. Finally, following the state-contingent method proposed by Quiggin and Chambers (2006), Mallawaarachchi *et al.* (2017) estimated the production function of dairy farms in Australia to analyse the effect of water allocation on farm performance. They accounted for endogeneity related to the change in the usage of productive inputs under different states of nature according to the productivity shocks. Moreover, they proposed a two-stage instrumental variables approach to correct the endogeneity bias due to self-selection.

4. DISCUSSION

Consistent with Just (2003), the results of this research confirm the low prevalence of risk-related agricultural production studies, showing the failure of risk researchers in convincing the broader profession of the importance of risk effects on farmers' decision-making. The vast majority of the articles using SFA in agricultural production did not consider risk despite its relevance in the field. For example, by omitting the keywords related to risk from the search query, the number of articles increases from 162 to 2595. Given that risk effects on productivity and technical efficiency are unavoidable, the stochastic production frontier must include risk sources to accurately account for and predict the technical efficiency of producers (Battese *et al.*, 1997). However, it was alarming to discover that relatively few articles account for risk by implementing a SFA approach. This may be attributed to the fact that this approach is still in development and the model is rather complex, regarding both the modelling and estimating procedure (Kumbhakar *et al.*, 2015).

It is worth noting that when the effects of risk are included in the model, the endogeneity sources are often ignored, resulting in biased estimates of parameters. Therefore, studies considering risk in the SFA approach seem to fail to represent the complexities of agricultural production modelling, such as accounting for endogeneity issues. Despite the methods of dealing with the endogeneity issues in production frontiers being well documented in the recent literature (Shee and Stefanou, 2014; Amsler *et al.*, 2016, 2017; Karakaplan and Kutlu, 2017; Latruffe *et al.*, 2017), most of the studies analysed in this review, do not generally account for endogeneity bias due to the input relationship with production shocks. In addition, other endogeneity sources may arise with the taking up of risk management tools or risk mitigation practices. According to Vigani and Kathage (2019), there are four possible cases. First, it is necessary to account for the possibility of reverse causality between the choice of adopting risk management instruments and productivity (Nelson and Loehman, 1987; Ramaswami, 1993). More productive farms, for example, are more likely to have the financial and managerial resources for risk mitigation (Enjolras *et al.*, 2012; Santeramo *et al.*, 2016). In addition, the self-selection problem needs to be addressed to avoid inconsistent estimates of risk mitigation tools on farm results. It is because, generally, the adoption is voluntary, and a particular strategy may be adopted by farms that have more advantages in adopting, i.e., they have different unobservable characteristics that may have an impact on both the adoption decision and performance such as risk aversion or perceived barriers to adopting risk management tools (Coletta et al., 2018; Di Falco and Veronesi, 2013; Giampietri et al., 2020). In addition, another potential source of endogeneity may arise from the substitution effect between risk management practices and input use since the adoption of risk-mitigating practices may change the level of input used (Ramaswami, 1992; Russo *et al.*, 2022). Finally, researchers need to account for omitted variables endogeneity by including the most adopted risk management tools. In fact, the estimates of risk mitigation practice effects may be biased because the total impact of adopting several risk mitigation practices simultaneously might not be equivalent to the sum of the influences when considering each strategy separately (Wu and Babcock, 1998). However, among the articles within the risk management thematic area, the few that dealt with endogeneity mainly considered the self-selection bias. None of these treated the endogeneity due to the input correlation with production shocks.

The lack of studies that deal with endogeneity by using the SFA approach in agricultural economics may be explained as follows. First, the stochastic frontier literature has largely ignored the advances made in the production function framework to control for endogeneity issues (Shee and Stefanou, 2014). Moreover, dealing with endogeneity is relatively more complex in the SFA approach than in the standard regression models. In fact, due to the nature of the error term in the stochastic frontier models, which include both the technical efficiency and statistical error terms, this is a relatively more difficult task (Karakaplan and Kutlu, 2017), which drastically reduces the number of researchers that are able to deal with these problems. Agricultural economists have to push for the advancement of more sophisticated methodologies to account for these issues since farming production is much more complex than other productive sectors. Indeed, agricultural production studies have to take into account the biological production cycle and environmental conditions, factors that are less relevant in other sectors.

Our findings show a gap in the literature in identifying a comprehensive approach capable of dealing with either risk and endogeneity concurrently when assessing farm productivity and technical efficiency in the SFA framework. This apparent deficiency in literature in the field may be related to the lack of consolidated knowledge in terms of standardized methodologies. As emerged in the current analysis, the authors applied different production frontier models by using several strategies to deal with both risk and endogeneity issues. The use of several statistical platforms leads to a situation where the routines are available in a fragmented way. For example, only certain softwares may be more appropriate to treat a specific problem. There is not yet a software where all the estimators are available (Kumbhakar *et al.*, 2020). Furthermore, despite its widespread use, only the most basic implementations of the SFA are available across the broad array of statistical platforms. As such, the lack of existing routines requires researchers to be able to program or code (e.g., creating new command or algorithms) to develop a frontier that accounts for all these factors.

5. CONCLUSION

With the increasing availability of data compared to the past and access to appropriate analytical methods/routines and statistical softwares, SFA may represent a useful approach to yield valuable results that can improve the effectiveness of policies in the agricultural sector. This is also imperative for the future development of well-suited policy instruments. To this end, a scoping literature review was conducted to overview the existing knowledge in farm risk analysis within the SFA framework. In particular, this article aimed to investigate the methods proposed in the literature to deal with endogeneity in SFA risk analysis.

The main limitation of this study is related to the inclusion of only peer-reviewed articles published in academic journals. However, this was deemed to be enough to highlight the gap in the literature. Therefore, for future studies of this domain, we suggest the review of grey literature as the approaches proposed in the study are still under development.

The findings of this research highlight the need for more studies that investigate the farm productivity and efficiency which also account for risk and endogeneity issues. This result is quite critical since the researchers' goal is often related to providing policy indications to enhance farm performance without focusing on the accuracy of data analysis. Neglecting risk and endogeneity in benchmarking studies may yield biased estimates and thus lead to incorrect policy recommendations. A comprehensive approach might help to achieve more accurate estimates that could yield recommendations that ensure improved productivity and technical efficiency of farmers. However, it is plausible to conclude that much still needs to be done in order to get a comprehensive approach to represent the complexity of agricultural production modelling.

Despite the relevant implications of risk and risk management tools in agricultural decision-making and economic performances, the SFA literature which focuses on these aspects is still underrepresented. Research should be focused on measuring the impact of the different sources of risk when assessing farm productivity and technical efficiency. This can ensure that policy recommendations are based on more representative results. As such policy formulation can integrate possible mitigation strategies needed to enhance performance.

Researchers should develop more accurate and sophisticated methodologies to take into account the complexity of the agricultural production modelling. Therefore, expert researchers are strongly encouraged to provide more information to ensure the replicability of their findings, for example, providing their own programming codes and guidelines for practitioners and policy analysts.

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Provision of public goods and bads by agriculture and forestry. An analysis of stakeholders' perception of factors, issues and mechanisms

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Abstract. The provision of public goods by agriculture and forestry has been a major topic of the agricultural policy debate in the EU. The objective of this paper is to investigate local stakeholder perceptions regarding the cause-effect relations between agriculture and forestry activities and a broad set of public goods and bads, and hence to contribute to the identification of improved policy options for a more efficient delivery of public goods from rural areas. The study presents an assessment based on 71 stakeholder questionnaires collected from seven case study regions in different EU countries. The survey was based on a list of the most relevant public goods and bads developed with the local stakeholders, and aimed to collect stakeholder perception of positive and negative impacts of agriculture and forestry on a range of environmental assets and their relationship with local drivers, socio-economic and cultural features, and policy mechanisms. The analysis shows that the role of agriculture and forestry in the provision of public goods is perceived as generally positive across the selected case study regions. Stakeholder opinions concerning the negative impacts on the environment were more divergent. In particular, differences regarding the impact of different socio-economic and cultural features, and policy mechanisms are evidenced. The results outline the importance of regulations. Also, payments for environmental services are considered relevant in particular for biodiversity, landscape, and water quality. Beside that, aspects such as expectations of society and the attitude of farmers towards the environment resulted noteworthy.

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Keywords: Common Agricultural Policy, Ecosystem services, public goods, stakeholders, transdisciplinary approach.
JEL codes: Q18, Q20.

HIGHLIGHTS

- The paper presents an analysis based on 71 stakeholder questionnaires collected from seven case study regions in the EU
- The study concerns the relation between public goods and factors, issues and policy mechanisms
- Results outline that in particular issues and mechanisms are influenced by the perception of public goods
- Regulations, payments for environmental services and environmental attitude of farmers and society result as the most relevant mechanism.

1. INTRODUCTION

Agriculture and forestry are the dominant forms of land-use, respectively covering 38% and 31% of the world's land surface (FAO, 2021). Beside the provision of raw materials such as food and timber, the society is increasingly demanding environmental and cultural services, most of which displaying public goods characteristics, from agriculture and forestry (Muradian & Rival, 2012; OECD, 2015). Also, 'disservices' (public bads) that are defined as ecosystem functions or attributes that generate negative impacts on human wellbeing, affect the wider society (Shackleton *et al.*, 2016). These negative impacts can result from agricultural and forestry activities (and in that case they overlap with the concept of negative externality) or might be related to natural processes (e.g. shrub encroachment, crop pests, pollen allergens cfr. Shackleton *et al.*, 2016 for a comprehensive definition of ecosystem disservices).

A wide range of policy tools (including incentives, regulations, information and training, etc.) can be used to induce farmers to adopt practices able to enhance the provision of services and reduce the generation of disservices from agri-ecosystems (Kuehne *et al.*, 2017). Nonetheless, the identification of efficient mechanisms in the context of the complex range of relationships between policy, institutions and actors, requires taking into account different factors that are often related to local-scale socio-economic and cultural features (Zasada *et al.*, 2012). Indeed, a consistent body of literature reports that the complex cause-effect relationships between the management of agri-ecosystems and the generation of benefits linked to public goods are connected to local-scale contexts (Hart *et al.*, 2011; Schaller *et al.*, 2018).

The provision of public goods by agriculture and forestry has been one of the main topics in the debate concerning the agricultural policy in the recent decades. The new programming period of the Common Agricultural Policy (CAP 2023-2027) of the European Union (EU) has confirmed the growing attention towards the environment: The CAP new "Green Architecture" aims to improve the effectiveness of EU agriculture in delivering public goods from rural areas through different tools such as enhanced conditionality, Agri-Environment-Climate Measures (AECM) and the Eco-schemes. The latter is a relevant novelty of the reformed CAP, introducing a set of measures that the Member States should include in Pillar I and that would work on a voluntary basis for farmers. The Eco-schemes, together with the enhanced conditionality, substitute the so-called 'greening' of the previous programming period and are aimed at harmonizing the mechanisms and the objectives of the Pillars I and II and -to some extent- should facilitate the uptake of agri-environment-climate practices by farmers (Runge *et al.*, 2022).

One relevant principle strongly underlined in the new CAP programming period is that a more effective design of AECM requires an adaptation fitting to the local contexts (EC 2021). Therefore, the role of national and sub-national institutions in the design and implementation of Eco-schemes and AECMs has been boosted in the CAP reform to facilitate a better targeting of agri-environmental policies based on the physical and ecological features of different areas. Nevertheless, the inclusion of the different socio-institutional structures (i.e. actors, networks, authorities, policy, etc.), their boundaries and interplay would allow a more comprehensive account of local needs and opportunities (Zasada *et al.*, 2017). Consequently, aspects related to the stakeholder perception of factors and issues affecting the generation of public goods in rural areas would potentially allow to increase the efficiency of the policy design by integrating the local-scale biophysical context with the complex socio-ecological processes affecting the provision of public goods (Lebel & Bennett, 2008; Schaller *et al.*, 2018).

The assessment of socio-ecological processes, that on one hand influence the supply of ecosystem services and on the other hand determine their demand (van Zanten *et al.*, 2014; Wolff *et al.*, 2015), can follow different analytical approaches. Biophysical approaches aim to assess public goods and bads through physical measures that can be spatially explicit. The results of such analyses are often characterized by a combination of very specific information that is difficult to scale-up on the aggregate (Marconi *et al.*, 2015). That hampers the policy design and reduces considerably its efficiency in particular when multiple public goods and bads are considered (Armsworth *et al.*, 2012). Despite there are methods and approaches of combining multiple public goods in the same area, examples of implementation are scarce and limited to case studies (e.g. Ungaro *et al.*, 2021). Other approaches try to attach values to public goods provision to support related decision-making, using either monetary (Tienhara *et al.*, 2021; Tyllianakis & Martín-Ortega, 2021) or non-monetary techniques (Targetti *et al.*, 2018). However, generalizations about value-generation processes and the identification of societal and stakeholder demands for multiple public goods and ecosystem services in a spatial explicit manner are very often complicate (Schwartz *et al.*, 2021). In addition, value assessments should include demand and supply that are difficult to observe separately one from each other (Wolff *et al.*, 2015). In practice, the relevance of public goods tends to mix up with the discrepancy between the desired level of public goods and the actual supply, but the quantitative assessment is challenging due to their cognitive and subjective nature[1] (Faccioli *et al.*, 2020), to the different types of use and non-use values perceived by people (Targetti *et al.*, 2021a) and to their variation at different spatial scales (Granado-Díaz *et al.*, 2020). In this sense, the sociocultural evaluation is an approach that is getting momentum (Martin-Lopez *et al.*, 2012). This approach is hinged on assessing how different people perceive and value the environment and the cognitions of wellbeing stemming from landscape. It therefore targets the relationship between society, public goods generation, and environment (Targetti *et al.*, 2021b). By embracing the complexity of human-nature relations, the sociocultural evaluation is less prone to incur in a mechanistic simplification of processes and institutions existing between society and nature and therefore is able to provide a more comprehensive assessment in comparison to other approaches (Muradian & Baggethum, 2021; Norgaard, 2010). Nonetheless, the heterogeneity of public goods perceptions involves the need of analyses able to identify typologies of such perceptions for supporting the design of policies (Soini *et al.*, 2012).

[1] Public goods perception is typically heterogeneous and depends on individual attitudes, experience and values. Also, cognitive processes such as beliefs and knowledge of ecological processes have a relevant influence on the perception and are therefore important aspects to be considered when assessing public goods (Adams, *et al.*, 2003).

The objective of the study is to investigate local stakeholder perceptions regarding the cause-effect relations between agriculture and forestry activities and a broad set of public goods and bads (PGBs) relevant to society in seven case study regions (CSR). We do so by providing a cross country comparison of perception from a sample of stakeholders based on a common analytical framework. In this paper, the concept of public bads is introduced to consider both positive and negative impacts of agricultural activities on a range of environmental assets such as landscape, water quality, biodiversity, etc. The analysis is based on the identification of groups of stakeholders featuring different PGB perceptions and the characterization of the group dissimilarities in terms of: i) drivers and/or forces that impact PGB provision (hereafter 'factors'), ii) local socio-economic and cultural features (hereafter 'issues') and iii) policy and governance mechanisms (hereafter 'mechanisms'). More specifically, the paper aims to: a) finding relations between PGB perceptions and stakeholder opinions regarding issues, factors and mechanisms that are considered able to foster public goods and/or reduce public bads; b) finding groups of stakeholders with convergent perception of PGBs; and c) discuss the potential of that information for the identification of improved governance options for rural areas.

The paper is structured as follows: the methodology and the description of the CSRs are reported in section 2. Section 3 illustrates the results and section 4 presents the discussion including the study implications for the design of agri-environmental policies. Section 5 concludes.

2. CASE STUDY REGIONS AND METHODS

2.1. Description of the case study regions

The CSRs were located in seven Member States (Finland, Spain, Italy, Germany, Romania, Bulgaria and Poland) to cover different geographical areas of the EU (North, South, West and East EU). Based on information collected from local stakeholders, one CSR was identified in each country to investigate areas featuring a relevant supply of public goods (cfr. § 2.2).

The Finnish CSR was North Ostrobothnia, in Northern Finland, featuring 88% of the land covered by forests. Typical elements of landscape are hills in the northeastern side, rivers and valleys in the western side, and flat peatland areas in the center of the region.

The Spanish CSR was Andalusia, in southern Spain, which hosts a wide variety of agroforestry landscapes, especially including olive groves (with more than 1.5 million ha), 'dehesas' agroforestry and livestock systems (around 1 million ha), winter rainfed cereal systems and different types of irrigated agricultural systems. While there are several hotspots related to PGs (e.g. biodiversity in dehesas) and bads (e.g. soil erosion in certain olive grove areas), there is a significant potential for improving PGB provision by agroforestry systems.

The Italian CSR was Emilia-Romagna, located in the north-eastern side of Italy. Agricultural areas cover around 60% of the region, which is mainly cultivated with intensive arable crops (42% of the utilized agricultural area). Agricultural systems in Emilia-Romagna are mostly oriented towards high-quality traditional and intensive production systems and have been characterized by a process of farm concentration (abandonment of small and marginal farms and increase in average farm size). Given the heterogeneity of the region, a wide range of PGB (e.g. biodiversity, amenities, water quality etc.) are relevant in relation to the different agricultural systems and practices.

The German CSR was located in the County of Märkisch-Oderland, Federal State of Brandenburg. The CSR is a natural park where forested areas are under nature conservation measures and are surrounded by agricultural areas. Relevant environmental aspects concern water scarcity, soil functionality (water retention and wind erosion), loss of habitats and biodiversity, and soil carbon stock linked to water management.

The Romanian CSR is the North-East Region, which is characterized by low productivity due to fragmentation of farmland ownership, aging workforce, migration of young people to urban areas and a high degree of poverty for small farmers. The main environmental problems are linked to deforestation, with implications on landslides and soil erosion issues.

The Bulgarian CSR is the South Central Region, where 48% of the land is represented by agricultural areas (mainly arable and grasslands) and 45% by forest areas. The region features a developed livestock sector and agriculture delivers many public goods which are highly valued in the region: agricultural landscapes, farmland biodiversity, water quality and availability. However, also public bads such as soil erosion affects 80% of agricultural areas.

The Poland CSR is the Podlasie region, where agricultural areas constitute 53% of the area and forests cover 31% of the territory. The region is predominantly rural and a significant number of municipalities include Natura 2000 sites. The number of farms recently declined by a rate of 14%. The farms are, on average, small and oriented towards high quality production. Environmental issues that are important include water quality pollution and biodiversity losses due to the recent intensification of agriculture and urban expansion.

2.2. Stakeholder survey and analysis

The survey was carried out to collect information regarding the perception of PGB provision from local agriculture and forestry systems across Europe, and identify the most relevant factors, issues, and the most useful policy mechanisms from the point of view of local stakeholders. The selection of stakeholders was made in all the CSRs following the same procedure. First, a list of relevant stakeholder types was defined, involving farmers and/or foresters, consultants and technicians assisting agricultural and forestry farms, public officers and decision-makers, NGO technicians, and researchers, with all of them focusing their working expertise on PGBs provided by agriculture and forestry. Second, according to the stakeholder types, a list of relevant stakeholders was identified.

The list of public goods and bads linked to agriculture and forestry was selected and refined through stakeholder workshops carried out in the seven selected Member States and in one EU-level workshop organized in Brussels. The workshops were aimed at gathering the views of regional and EU-level stakeholders regarding the notion and the ranking of public goods and bads from agriculture and forestry systems, and issues affecting their provision and demand. A list of 29 different public goods and bads was developed in the workshops. Public bads were, in general, not considered as something conceptually different from public goods and were referred to low or inadequate supply levels of public goods (e.g. for instance, the public bad related to biodiversity was 'biodiversity loss'). In other cases, public bads referred to aspects which could be understood as activities or actions generating public bads, such as pollution. The list of 29 PGBs was afterwards refined taking also into account the typology of most relevant public goods linked to the agricultural sector in the EU as proposed by Cooper and colleagues (2009; cfr. also ENRD, 2010). Accordingly, eight PGB types related to ecosystem capital (Rural landscape, farmland biodiversity, water quality and availability, soil functionality, climate stability, air quality, resilience to flooding and fire) and two related to social capital (rural vitality, and animal health) were selected among the 29 PGBs (Table 1; cfr. Annex A; Novo *et al.*, 2016).

A further objective of the country-level workshops was to map and delimit the CSRs in which to carry out

Table 1. List of public goods and bads considered in the survey (cfr. Annex A).

Public goods	Public bads
Landscape and scenery	Landscape degradation
Farmland biodiversity (animal and vegetal)	Biodiversity losses
Water quality and availability	Water resources pollution and depletion
Air quality	Air pollution
Soil functionality	Soil erosion
Climate stability	Climate degradation
Resilience to flooding, landslides and fire	Increase of flood and wildfire risk
Rural viability and vitality	Degradation of abandoned land
Production quality and security (food, timber, energy)	Poor productions quality and distribution
Farm animal health and welfare	Degradation of animal health and welfare

the subsequent stakeholder survey focusing on PGBs and outline a list of issues, factors and mechanisms affecting the public good delivery. To this end, areas featuring relevant supply of public goods were mapped during the workshops to identify 'hotspots' areas and the main issues in terms of public goods supply and demand, and the potential related criticalities (Tindale *et al.*, 2018).

A questionnaire was developed to be submitted to local stakeholders in the 7 selected CSRs. In the questionnaire, the stakeholders were asked to score the relevance of the ten selected PGBs in their CSR. First of all, the relevance of the public goods delivered by agriculture and forestry systems was assessed on a 0-9 scale, then they were asked to score on the same scale the public bads. Thus, each stakeholder provided an overall 20 scores for the relevance of PGBs. For each PGB, the stakeholders were then asked to indicate whether the different factors, issues, and mechanisms were relevant or not in their CSR (Table 2).

One-hundred-one local stakeholders were invited in the 7 CSRs to participate to the survey with a request to fill-in a multiple-choice questionnaire. The survey was filled-in by a total number of 71 respondents in the seven CSRs 68% out of which indicated 'agriculture' as their area of expertise, whereas 32% indicated 'forestry'. The composition of the sample according to the professional categories represented by the respondents is synthetized in Table 3, showing that stakeholders are mostly researchers working in the field of agriculture and forestry or related (38% of the total sample) or public officers from regional or national agencies (30%) (Table 3).

Concerning the composition of the sample, the Italian CSR, Emilia-Romagna region, was the most represented region (23% of the total sample), followed by the Romanian (21%), Bulgarian and Spanish (14% each), Polish and German (10% each) and Finnish CSRs (8%).

2.3. Statistical analysis

The identification of a typology of stakeholder perception towards PGBs was carried out performing a hierarchical cluster analysis based on the scores attributed by the stakeholders to the 20 PGBs. The cluster analysis was preceded by a principal component analysis (PCA). The output of the PCA (scores on the PCA axes) was employed for the cluster analysis (Ward agglomeration method, Manhattan distance metric). This analysis is often employed to explore heterogeneous opinions of respondents (e.g. Soini *et al.*, 2012). Previous applications of such an approach have also shown its useful application in studies focusing on agri-environmental policy (e.g. Maton *et al.*, 2005; Gómez-Limón *et al.*, 2013)[2]. The identification of the clusters was supported by the analysis of the dendrogram structure (Appendix B) to identify how the cases (i.e. the stakeholders) grouped together. An inertia analysis was employed to support the visual identification of the optimal number of clusters. That analysis is based on the within-cluster sum-of-squares calculated for each partition and indicates the partitioning of the dendrogram with the higher relative loss of inertia (inertia of cluster n+1/ inertia of cluster n). According to that, the inertia analysis identifies the

[2] Analyses combining PCA with a hierarchical clustering is often used in social sciences to identify the main variables 'explaining' a database variability and describe groups of cases accordingly. In particular, the PCA outlines the variables able to explain the major part of the variance on the different axes, the cluster analysis is then performed on the scores attributed to these variables. The approach is therefore able to reduce considerably the 'noise' that is usually present in database concerning individuals' perceptions. Regarding the use of such approaches in perception-related surveys, some examples are reported in Husson *et al.*, 2010; Soini *et al.*, 2012; Targetti *et al.*, 2020 and 2021a. The objective is reducing the 'noise' which generally affects database regarding opinions or cognitive-related processes and outline trends or tendencies in the dataset. That procedure is usually at the base of the interpretation of the information conveyed or formulation of policy recommendations.

Table 2. List of factors, issues and mechanisms devised in the local and EU-level stakeholder workshops and considered in the survey.

Factors	Issues	Mechanisms
Public goods are a direct results of land management by farmers and foresters complying with the environmental regulations	Public goods and bads are still theoretical concepts, society has no perception of the role of farmers and foresters as land managers	Increase financial support to farmers and foresters
Public goods are direct result of agriculture and forestry fostered by CAP funding	Inadequate funding for compensation of farmers and foresters adopting sustainable practices	Implement payments for environmental services
Public goods are direct result of the increasing pressure and control exerted by society on farmers and foresters	Conflicts of interest and uses between different stakeholders	Implement new market-based incentives
Public goods are direct result of market demand for healthier, more sustainable agricultural and forestry products	Development and trade-offs between different land uses	Promote farmers' and foresters' education to sustainability
Public goods are direct result of technological advancement and innovation in agriculture and forestry	Problems related to the urban sprawling, rural land abandonment	Adapt compensation schemes and regulations to the global market
Public bads are mostly unintended by-products from agricultural and forestry activities, (direct result only in absence of compliance with the law)	Public access to public goods; land tenure and property issues	Adopt more efficient land use plans
Public bads s are never a direct result of agriculture and forestry, which do not pollute the environment or to damage the society intentionally		Pioneer/foster cross-compliance in all public subsidies
Public bads are a direct result of land management choices exerted by farmers and foresters (e.g. practicing intensive agriculture)		
Public bads are a consequence of the absence of adequate compensation schemes to farmers and foresters		
Public bads are caused by the rising land-abandonment in rural areas		
Public bads emerge from the competition between regions/ countries forcing farmers and foresters to lower the sustainability of productions		

Table 3. Composition of the sample of stakeholders and shares of job categories.

	N.	%
Research/ academics	27	38%
Public officers	21	30%
NGOs	9	13%
Consultant/ agronomists	8	11%
Farmers/foresters (incl. agri-food firms and representatives of producers associations)	6	8%

classification where a further cluster formation does not provide an advantage in terms of data description.

The information regarding the relevance of factors, issues and mechanisms was analyzed with the Shannon-Weaver indicator (H index) as following:

$$H=-\sum p_i \times \ln p_i \quad (1)$$

Where p_i indicates the frequency with which a variable (factor, issue or mechanism) was rated as relevant for a specific PGB in that cluster. The H index is a measure of the information entropy and was employed to indicate if specific factors, issues or mechanisms were considered relevant for specific PGBs (i.e. highlighting a low entropy) or otherwise there was not specific indications emerging from the stakeholders (i.e. high entropy: all factors, issues or mechanisms considered relevant).

3. RESULTS

3.1. Relevance of public goods and bads

In general, public goods linked to agricultural and forestry systems were perceived as relevant in the CSRs (Figure 1). Indeed, the average score ranged between

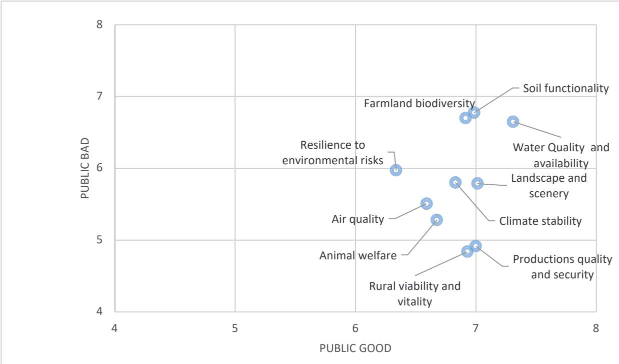

Figure 1. Stakeholders' perception of public goods and public bads provided by agricultural and forestry systems in the 7 CSRs. The rating is reported on a 9 point scale and related to the ten environmental categories included in the study.

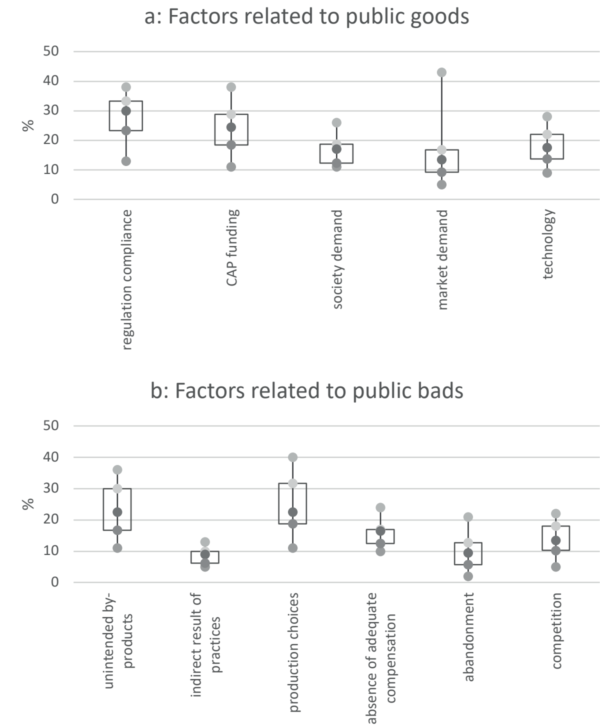

Figure 2. Perception of the stakeholders concerning the relevance of the factors linked to PGBs across the 7 CSRs and for the 10 PGBs: Boxplot of factors related to public goods (a) and public bads (b) provision from agricultural and forestry systems. Grey points in each plot represent 10th, 25th, 50th, 75th, and 90th percentiles, bottom to top.

6.34 for 'Resilience to Flooding, Landslides and Fire' and 7.31 for 'Water Quality and availability' (out of a maximum of 9). Perception of public bads was lower in comparison to public goods. In particular, public bads related to 'Rural viability and vitality' and 'Productions quality and security' were considered the least important (range 4.8-4.9). On the contrary, the relevance of public bads linked to the reduction of 'Farmland biodiversity', 'Soil functionality' and 'Resilience to environmental risks' was significant. As evidenced in Figure 1, a greater variability characterized the scores attributed to public bads. That is also outlined by higher standard deviations for public bads (range 2.15-2.83) in comparison to public goods (range 1.67-2.37) (Appendix C). Public goods perceptions across the CSRs did not result significantly different. On the other hand, public bads perception were significantly different across the CSRs (with $p<0.05$) for all the PGBs considered in the study except for 'Degradation of rural viability and vitality', 'Reduction of climate stability' and 'Reduction of resilience to environmental risks'.

3.2. Factors, issues, and mechanisms linked to public goods and bads

The results about the most important factors considered as relevant for the different PGBs across the seven CSRs are shown in Figure 2. The results show that the most important factors relate to the complying of farmers and foresters to the environmental regulations for public goods and the land management decisions taken by farmers and foresters for public bads (with an across-CSRs average of 30% and 25% of all PGBs impacted by these factors respectively). Specific PGBs that were considered particularly related to regulations were farmland biodiversity and water quality (54% of stakeholders indicated regulation as a relevant factor for these PGBs; Appendix D). Similarly, the CAP funding was considered a significant and positive factor for biodiversity protection and maintenance of rural viability and vitality by 54% of stakeholders. On the other hand, production choices were indicated as a factor specifically related to farmland biodiversity depletion by 56% of stakeholders. The stakeholders' opinions concerning the factors were not significantly different across the CSRs. Two notable exceptions were 'Public goods are direct result of market demand for healthier, more sustainable agricultural and forestry products' that was significantly different with $p<0.01$ and the factor 'Public bads emerge from the competition between regions/countries forcing farmers and foresters to reduce the sustainability of productions' with $p<0.05$.

The relevance of the issues for the ten PGBs was rated between an average of 18% and 33% (Figure 3). In particular, the perception of the role of farmers and foresters as land managers was considered the most rel-

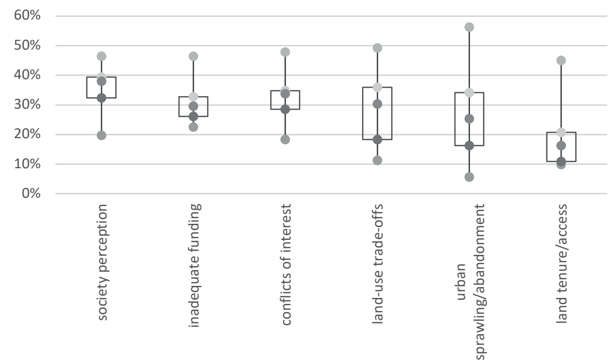

Figure 3. Boxplot of issues related to PGB provision from agricultural and forestry systems: Average stakeholder perception concerning the relevance of the issues across the seven CSRs and for the ten PGBs. Grey points in each plot represent 10th, 25th, 50th, 75th, and 90th percentiles, bottom to top.

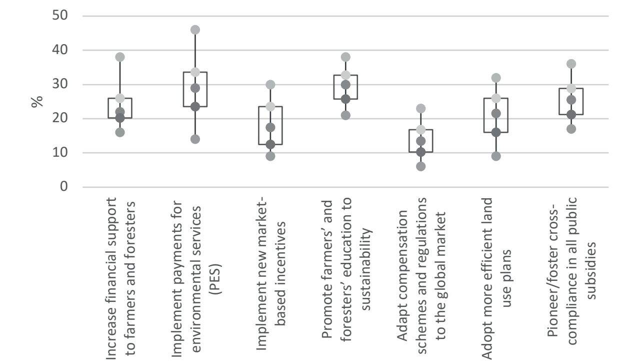

Figure 4. boxplot of mechanisms related to PGBs provision from agricultural and forestry systems . Average perception of the stakeholders concerning the relevance of the mechanisms across the seven CSRs and for the ten PGBs. Grey points in each plot represent 10th, 25th, 50th, 75th, and 90th percentiles, bottom to top.

evant issue, whereas issues linked to land tenure and access were considered on average the least important. Even though urban sprawling and land abandonment was not considered among the most relevant issues for PGBs, that issue was the most important affecting 'Landscape and scenery' (Appendix E). In the case of public bads, 'Inadequate funding' was perceived as the most important issue and in particular 45% of stakeholders considered that as relevant for biodiversity degradation[3]. Likewise for factors, stakeholders' opinions over the issues considered were quite homogeneous across CSRs, except for 'Urban sprawling and abandonment' and 'Development and trade-offs between different land uses' for which statistical significant differences were found between the CSRs (at 0.05 and 0.01 levels, respectively).

According to the stakeholders, the most relevant mechanisms to improve public goods and reduce public bads were the implementation of payments for environmental services (PES) and the promotion of farmers' and foresters' awareness of sustainability (education). These mechanisms were considered effective for a range of different PGBs, but PES were rated as particularly effective for biodiversity and landscape (62% and 53% of stakeholders on average rated PES as relevant for biodiversity and landscape; Appendix F). Interestingly, the mechanism 'Adapt compensation schemes and regulations to the global market' was considered as the least effective mechanism to foster public goods and reduce public bads. Concerning the difference between regions, PES and 'Adopt more efficient land use plans' were significantly different across the seven CSRs considered ($p<0.05$; Appendix G).

3.3. Cluster analysis. Finding groups of stakeholders with convergent perception of PGBs

The cluster analysis performed on the PCA scores outlined four clusters (Appendix B). The largest cluster (Cluster 2) included 37% of stakeholders characterized by stating high scores for all PGBs (with overall average scores of around 8 out of 9 for both public goods and public bads; Table 4). Noteworthy, public bads were relevant and higher than in the other clusters. The second largest cluster (Cluster 3) grouped 25% of stakeholders was characterized by the perception of landscape as the most relevant public good (average score of 7.7) and biodiversity depletion as the most important public bad (scoring 6.9) connected to agricultural and forestry systems. Also, PGBs linked to resilience to flooding, landslides and fire and air quality were considered the least relevant, with scores within the range of 3.6-4.6. The third largest cluster (Cluster 4; 24% of stakeholders) was composed by stakeholders who stated the overall lowest scores for PGBs (5.5 for public goods and 4.2 fo public bads), considering rural viability as the most relevant public good and soil erosion as the most critical public bad (scoring 6.7 and 6.2, respectively). In this cluster, water and production quality were considered the least relevant public good and public bad respectively (scoring 4.3 and 5.1). Finally, Cluster 1 included 18% of stakeholders. In that cluster, the stakeholders perceived a high relevance of public goods (7.2) compared to bads (4.5), indicating soil functionality as the most relevant public

[3] More details concerning the differences between the stakeholder perception have been reported in the discussion section.

Table 4. Average scores of PGBs in the four identified clusters. The PGBs that in each cluster were reported more frequently as relevant in the stakeholder opinion are in bold.

Variable	Cluster 1-"Positivists"		Cluster 2-"Holistics"		Cluster 3-"Naturalists"		Cluster 4-"Agrarians"	
% of stakeholders	18		37		24		21	
	PGs	PBs	PGs	PBs	PGs	PBs	PGs	PBs
Landscape and scenery	6.6	3.3	7.6	8.0	7.7	5.4	5.8	4.3
Farmland biodiversity	7.8	4.8	7.7	8.2	7.4	6.9	4.6	5.4
Water quality and availability	8.1	4.2	8.7	8.3	7.4	6.6	4.3	5.1
Air quality	6.8	5.7	8.5	8.2	4.6	3.9	5.4	3.5
Soil functionality	8.2	3.8	8.7	8.0	5.8	5.9	4.5	6.2
Climate stability	7.5	6.4	8.3	7.9	5.5	5.1	5.5	4.5
Resilience to flooding landslides and fire (%)	7.8	4.8	7.9	8.2	3.6	3.8	5.6	4.1
Rural viability and vitality	6.1	4.5	8.0	7.3	6.4	2.8	6.7	3.7
Quality and security of products (food. timber. energy)	6.8	3.3	8.1	7.3	6.1	3.5	6.5	2.6
Farm animal health and welfare	6.6	4.2	7.9	7.6	5.9	4.4	5.6	3.0
Overall average score	7.2	4.5	8.1	7.9	6.0	4.8	5.5	4.2

good (scoring 8.2) and the deterioration of climate stability as the most relevant public bad (scoring 6.4) produced by agriculture and forestry systems. In cluster 1 on the contrary, public bads related to landscape and production quality were perceived as the least important (both scoring 3.3). Considering the results, we propose the following cluster labelling: *C1-Positivists, C2-Holistics*, *C3-Naturalists* and *C4-Agrarians*.

The four clusters outlined a relation with some of the CSRs as presented in Appendix G. In particular, cases from the German and Spanish CSRs were more often classified in C3-Naturalists and C4-Agrarians, respectively. C1-Positivists and C2-Holistics, on the contrary, showed a less clear relation with a specific CSR, though stakeholders from the Italian CSR were more likely C1-Positivists and Romanian CSRs were more likely C2-Holistics.

Figure 5 shows the Shannon-Weaver index of information entropy for factors, issues, and mechanisms for the different clusters. The classification provided by the cluster analysis allowed to reduce the information entropy and therefore provided indications about the relevance of specific issues and mechanisms for the different PGBs: As shown in figure 5, the uncertainty conveyed by the stakeholders concerning issues and mechanisms in connection with the different PGBs was significantly decreased. On the contrary, the information entropy regarding the factors linked to PGBs was not affected significantly with the cluster analysis. According to the Shannon-Weaver index, C2-Holistics showed the highest entropy for issues and mechanisms, indicating a lower capacity to discriminate between these for the improvement of PGB provision from agriculture and forestry. The cluster analysis enhanced the information quality in particular for C1-Positivists and, to a lesser extent, C3-Naturalists and C4-Agrarians, which recorded a significant lower entropy of the information across issues and mechanisms in comparison to C2.

4. DISCUSSION

In general, the average scoring of public goods linked to agricultural and forestry systems in the 7 CSRs was higher than the perception of public bads. That points to an overall positive perception of the role of agriculture and forestry activities in providing environmental services, but that was also linked to the selection of CSRs with relevant levels of public goods supply. In particular in the selected CSRs, public goods such as production quality and quantity, and rural vitality clearly prevail compared to the public bad one. This may reflect a general perceived efficiency of agriculture and forestry in providing those public goods (Villanueva *et al*., 2014; Novo *et al*., 2016). The results also indicate that the rating of public goods such as biodiversity, soil functionality, and resilience to environmental hazards, was very close to the rating of public bads. That denotes contrasting impacts for these environmental categories that are likely linked to different agricultural practices or systems and therefore highlights aspects where agri-environmental policies may play a more relevant role.

Even though public bads perception was generally low, its variability across the CSRs was more promi-

Figure 5. Shannon-Weaver index of information entropy. Boxplot of the clusters and ANOVA: Boxplots with different letters indicate significant differences of H' between the clusters with p<0.05 (Tukey HSD test for significant difference between clusters with**=p<0.01; *** p=<0.001; ns= not significant; i.e. cluster indicated with 'a' is different from 'b', cluster indicated with 'ab' are not different from 'a' and 'b').

nent in comparison to public goods. In other words, the analysis indicates that agriculture and forestry systems are perceived as relevant "providers" of a wide range of public goods, whereas differences across the CSRs are more evident when considering the negative impacts. That points to an appropriate consideration of public bads and supports the stream of literature highlighting the usefulness of ecosystem disservice analyses for disentangling the dynamics taking place in different rural regions (Blanco *et al.*, 2019; Targetti *et al.*, 2021b; Zabala *et al.*, 2021). Nonetheless, the inclusion of CSRs featuring agricultural systems that provide significant public bads would be necessary to bring clearer insights in that respect.

The selectd CSRs were characterized by different agricultural and forestry systems, but that did not implicate siginificant differences related to PGBs. In that respect, the classification based on the cluster analysis allowed to increase the informative value conveyed by the stakeholders and highlighted significant differences across the clusters concerning issues and mechanisms. On the contrary, the perception of factors linked to PGBs was rather homogenous between the clusters. That evidence highlights how issues and mechanisms may have a different relevance even though the factors linked to PGBs are rather similar. For instance, the important role of factors such as regulations and the CAP in promoting public goods was a clear outcome of the analysis. In contrast, the implementation of mechanisms such as payments for environmental services was rated as particularly effective for public goods such as biodiversity and landscape. Similarly, inadequate funding was considered as an issue with negative consequences for specific public goods such as farmland biodiversity, rural viability, and production. That confirms that the design of large scale policies for PGBs is complicate because of the different local-scale and socioeconomic features as supported by a range of studies (e.g. Armsworth *et al.*, 2012; Schaller *et al.*, 2018). Our results show that the consideration of mechanisms and issues would help to target the PGBs that are at stake in the different regions and improve the implementation of agri-environmental policies. Indeed, some general trends regarding mechanisms can be highlighted. For instance, the promotion of farmers' and foresters' awareness of sustainability issues resulted as a very effective mechanism for a range of different PGBs. If on one hand the stakeholders underlined aspects related to human and social capital like education, on the other hand they highlighted a scarce belief in market-related mechanisms such as adapting PGB schemes and regulations to the global market and market-based incentives. The latter, though, was rated as a relevant mechanism for improving production quality. In a nutshell, market-related mechanisms link better to specific PGBs that are considered more relevant for consumers (e.g. food production and animal welfare), other PGBs relating for instance to water, soil, landscape etc. require more refined mechanisms such as PES and cross-compliance of public subsidies. Contrarily, the scope of mechanisms designed to enhance education to sustainability of farmers and foresters is rated as effective on a more general level.

Concerning the issues connected to PGBs, tools targeting human capital were confirmed as important. For instance, societal perception of the role of farmers and foresters was considered the most relevant issue. That reiterates the opportunity to consider "soft" aspects like education ,social benefits and the acknowledgment of the role of land managers in environmental protection. Other issues that reached a high ratings in connection to specific PGBs was urban sprawling and land abandonment for their impacts on landscape and rural viability. On the contrary, the issue 'Public access to public goods, land tenure and property' was usually included among the least relevant issues.

Concerning the perception of factors, regulations were acknowledged as the most important for the delivery of public goods. CAP funding was also perceived as very relevant in particular for specific PGBs such as biodiversity and rural viability. On the other hand, the role of farmers' decisions and the unintended effects of those decisions were perceived as the most important factors. Those results outline a very traditional view of agri-ecosystems where farming activities generate externalities that policies need to tackle through classical stick-and-carrot tools. Technology, on the contrary, was not perceived as a factor able to improve the provision of PGB from rural areas. Exceptions concerned water and production quality. That is likely linked to the availability of technologies like for instance drip irrigation that are well-known for their potential positive effects, whereas for other public goods like biodiversity the potential of technology in helping the transition towards agro-ecological solutions is still less palpable (Bellon-Maurel & Huyghe, 2017).

In terms of policy implications, the limited number of stakeholders and regions that were included in the survey (71 stakeholders in 7 CSRs) makes difficult to generalise the results. Though, the work was carried out in a good range of different agricultural and forestry areas, located in North, East and Southern parts of the EU. Even though with limitations, the study can therefore highlight some trends and interesting aspects on the connection between agriculture and forestry, and the supply of PGBs in EU. The results support the usefulness of mixing different tools taking into consideration their different capacity to deal with different PGBs. On one hand regulations seem to guarantee high levels of efficiency, on the other hand a mix with tools targeting information and education are also necessary. Beside the importance of policy mix, that result also confirms that the configuration and design of the different tools together is important (Fraser and Campbell, 2019). Nevertheless, this work cannot provide insights on aspets related to the design of different policy mixes as the study focused on the relevance of the mechanisms for the different PGBs and not on the configuration of different mechanisms together. A further interesting aspect regards the reflection on the temporal dimension. Even though the survey did not explicitly consider the time range, the results outline a dicrepancy between issues, factors and mechanims that accrue in the long term (e.g. human capital related) and others that denote a more immediate impact (such as regulations and payments for environmental services). However, that observation would need confirmation through an ad-hoc study focused on these aspects.

From a governance perspective, several considerations can be raised. First of all with specific reference to sectorial policies like the CAP, the relevance of incentives to support (reduce) the supply of public goods (bads) results as paramount. Indeed, a general skepticism emerges concerning the possibility to improve public goods such as biodiversity or other environmental services relying on market-related mechanisms only. Likely, the importance of supporting (e.g. biodiversity) and regulating services are considered too complex to fit easily to society awareness. That involves the perceived necessity to intervene with subsidies to complement the rationale of the market demand-supply mechanism. In that regard, the new CAP architecture (REG 2021/2115)[4] could tackle that aspect. For instance, the higher rate of funding earmarked for environmental objectives (e.g. the eco-schemes) and the enhanced conditionality requirement could match with increasing the CAP targeting towards environmental objectives. Beside incentives, the role of regulations as necessary tools to ensure an adequate level of public goods supply is also reported. However, it seems obvious in the stakeholder perception that the availability of budget for incentives and regulations for PGBs is not enough without a more 'horizontal' approach of the policy design (Hodge, 2001). Fostering cross-compliance of public subsidies was for instance a mechanism that was rated as very important for several PGBs. In other words, the adequacy of a policy framework focusing on environmental objectives is necessary but not sufficient if a local-scale dialogue with other land-use-planning institutions and a wider range of local economic sectors is not established.

[4] Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the common agricultural policy (CAP Strategic Plans); https://eur-lex.europa.eu/eli/reg/2021/2115/oj - access in all EU languages

The study also highlights that a more efficient governance of PGBs is forcedly related to human capital. Knowledge, perception, ability, are for instance some of the farmers' and foresters' education objectives that need to be considered and promoted in consideration of long-term goals (Knowler and Bradshaw, 2007). The difficulty is clearly related to the necessity to focus short-term targets taking also into account the long-term objectives (Janssen and Anderies, 2007). For instance, the development of new PES schemes was considered relevant. But the implementation of innovative payment types also needs to take into account the socioeconomic context. In other words, if innovative solutions will be more and more necessary their success also depends on the capacity, interest and motivation of farmers to uptake such solutions (Raina *et al.*, 2021). Tools fitting to the improvement of human capital are therefore relevant, but the time range needed is usually long and a constant adaptation and coordination with regulations and incentives is needed.

5. CONCLUSIONS

The work presents the results of a survey carried-out in 7 CSRs and collecting opnions from 71 stakeholders. The work covered a range of different agricultural/forestry systems located in North, East and Southern parts of the EU that were selected for their particular supply of public goods. Even though with limitations, the study can therefore highlights some trends and interesting aspects on the connections between agriculture and forestry, and PGBs in EU.

Overall, the perceived impacts on PGBs linked to agriculture and forestry were positive: this is consistent across regions and stakeholders, whereas more remarkable differences between the stakeholders were evident for public bads. On one hand, that outcome confirms that the selected CSRs were 'hotspots' of public goods. On the other hand, assessing aspects related to public bads is a potential pathway of research to shed light on differences and opportunities for the design of local-scale agri-environmental policies (Blanco *et al.*, 2019; Targetti *et al.*, 2021a). In that regard, the selection of CSRs denoting a significant supply of public goods is however a limitation of the study. The inclusion of CSRs featuring a wider set of PGB supply would therefore be necesssary to deepen the aspects related to public bads.

The results clearly point to regulation compliance and subsidies as relevant factors for the maintenance and improvement of a range of public goods. The CAP in particular is confirmed among the most relevant factors but the opinion of the stakeholders is rather differentiated according to the different PGBs. This can be related to a less clear perception of effectiveness of voluntary schemes, but in part it is also very likely associated to the higher complexity of that policy approach and the consequent difficulty in assigning clear impacts on specific PGBs. That is consistent with current debates that concerns for instance the role and design of subsidies for the conservation and promotion of farmland biodiversity (Pe'er *et al.*, 2022).

A general convergence regards the impact of factors on PGBs. Conversely, a different consideration of mechanisms and issues was evidenced and related to the different perception of stakeholders towards PGBs. The classification provided by the clusters analysis allowed to understand the configuration of issues and mechanisms that were considered relevant in connection with the different PGBs. For instance, market processes and society demand were more relevant for specific public goods such as production quality and security, and animal welfare, whereas to a lesser extent to climate stability. This in part explains the relevance attributed to market-related mechanisms for those PGBs. Instead, more articulated tools such as payments for environmental services were considered necessary for public goods such as landscape, biodiversity, water quality, etc. The disconnection between society demand and supply of environmental services is fundamentally an issue that involves awareness of processes underpinning such services, the adequacy of markets to stimulate specific services, and the trade-offs that inevitably incur between levels of ecosystem services supply (Adams, 2014). In this study, we have evidenced that different stakeholders have different views and opinions but further evidence would be necessary to understand whether such differences might be related to CSR features or agricultural systems.

Beside regulation and subsidies, soft aspects leveraging on the environmental attitude of farmers and society are considered important across the different CSRs and for the different public goods. Surely, these aspects accrue on longer time ranges but likely their perceived relevance denotes a scarce attention or inefficiencies of the current agrienvironmental policy framework towards those topics. Even though the study did not evaluate different policy mixes, a message emerging from the analysis supports the need of considering instruments addressing different temporal and spatial scales. On the one hand regulations are considered effective for a wide set of public goods and across the different CSRs. On the other hand, the effectiveness of incentives depends on the type of public goods and local scale issues. The role of knowledge, awareness and education in general is considered relevant for enhancing the adaptation capacity of a socio-ecological system (Janssen and Anderies, 2007). Therefore, tools targeting social and human capital should also be taken into account even though their impact will likely span in the long-term.

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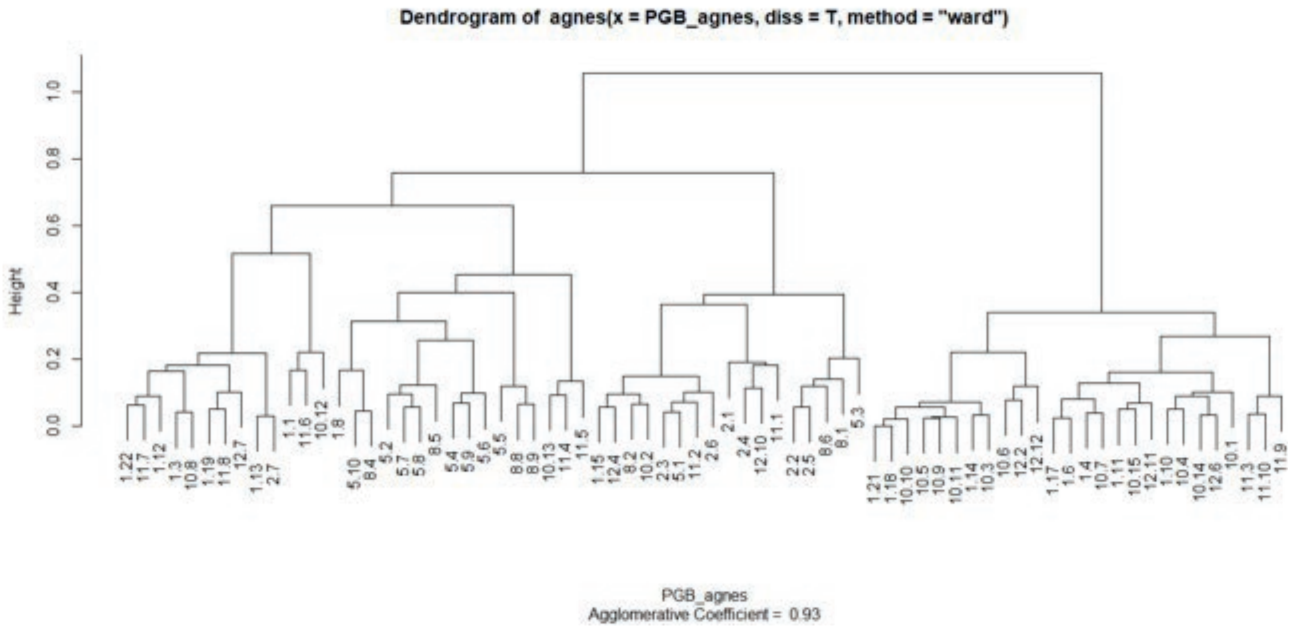
APPENDIX A

List and description of PGBs as developed with the stakeholders.

	Category	Related Public Goods	Related Public Bads
1	Rural Landscape	Beauty access Naturalness (sounds & scents) Health & wellbeing Tranquility Tourism Educational & recreational values Connectedness & spiritual values	Landscape degradation Land fragmentation Barriers to recreation Clear-cut forest areas
2	Farmland Biodiversity	Pollination Habitats Wild berries and mushrooms Games Local varieties of plants and animals Protection against pests Picking fruits	Pest & diseases Increase of dangerous wild animals Pollination reduction
3	Water availability	Sustainable land management Resilience to drought	Intensification Natural resources consumption
	Water quality	Sustainable land management	Intensification Water Pollution Intensification Health problems
4	Air quality	Health, & wellbeing Sustainable land management	Intensification Air pollution Health problems
5	Soil functionality	Sustainable land management Carbon storage Water retention Geodiversity Climate change adaptation and mitigation	Soil erosion Soil pollution Intensification
6	Climate stability	Carbon storage GHG emissions Carbon Sink	Intensification
7	Resilience to flooding, landslide and wildfire	Sustainable land management Water flows regulation Climate change adaptation	Flooding
	Resilience to fire	Sustainable land management Climate change adaptation	Wild fire
8	Rural viability/vitality	Cultural heritage Local identity Land & Infrastructure maintenance Creation of rural jobs Land stewardship Connectedness & spiritual values	Land abandonment Culture loss Poverty Poor land management Safety / vandalism
9	Food, energy and timber security and quality (local supply)	Energy supply Food security & quality Sustainable land management Employment Forest quality	Poor food quality & distribution Outsourcing production Deforestation Natural resources exploitation
10	Farm Animal health/welfare	Foraging & hunting Pasture and grasslands Sustainable land management	Intensification Health problems

APPENDIX B



Cluster dendrogram.

APPENDIX C

Average perception of PGBs relevance and standard deviation. Public goods perception Public bads perception were significantly different across the CSRs (with $p<0.05$) for all the PGBs considered in the study except for 'Degradation of rural viability and vitality', 'Reduction of climate stability' and 'Reduction of resilience to environmental risks'.

	Public goods perception*		Public bads perception**	
	Average score	St. dev.	Average score	St. dev.
Landscape and scenery	7.01	1.67	5.79	2.68
Farmland biodiversity (animal and vegetal)	6.92	1.97	6.70	2.25
Water quality and availability	7.31	2.21	6.65	2.33
Air quality	6.59	2.33	5.51	2.83
Soil functionality	6.99	2.29	6.77	2.15
Climate stability	6.83	2.15	5.80	2.56
Resilience to flooding, landslides and fire	6.34	2.37	5.97	2.79
Rural viability and vitality	6.93	1.89	4.84	2.76
Productions quality and security (food, timber, energy)	7.00	2.00	4.92	2.73
Farm animal health and welfare	6.68	1.98	5.28	2.55

*Difference between case study regions not significant
** difference between case study regions significant with $p<0.05$ except for 'Degradation of rural viability and vitality', 'Reduction of climate stability' and 'Reduction of resilience to environmental risks'.

APPENDIX D

Heathmap of the perception of relevant factors for the different PGBs.

	Relevant for public goods				
	Regulation compliance	CAP funding	Technology	Society demand	Market demand
Productions quality and security (food, timber, energy)	42%	41%	39%	34%	61%
Farmland biodiversity (animal and vegetal)	54%	54%	23%	24%	24%
Farm animal health and welfare	44%	35%	25%	37%	46%
Resilience to Flooding, Landslides and Fire	42%	25%	18%	17%	8%
Water Quality and availability	54%	28%	38%	27%	17%
Landscape and scenery	32%	39%	15%	24%	21%
Soil functionality	48%	34%	31%	15%	14%
Rural viability and vitality	18%	54%	24%	17%	23%
Climate stability	28%	23%	13%	18%	7%
Air quality	34%	15%	31%	25%	13%

	Relevant for public bads					
	Production choices	Nnintended by-products	Absence of adequate compensation	Competition	Abandonment	Indirect result of practices
Productions quality and security (food, timber, energy)	31%	15%	24%	31%	14%	14%
Farmland biodiversity (animal and vegetal)	56%	48%	34%	25%	13%	15%
Farm animal health and welfare	30%	21%	23%	23%	7%	13%
Resilience to Flooding, Landslides and Fire	32%	31%	14%	7%	18%	8%
Water Quality and availability	45%	31%	20%	30%	3%	7%
Landscape and scenery	44%	51%	24%	15%	23%	14%
Soil functionality	48%	44%	24%	25%	17%	7%
Rural viability and vitality	15%	15%	17%	10%	30%	10%
Climate stability	25%	38%	27%	15%	11%	18%
Air quality	25%	32%	14%	14%	7%	13%

APPENDIX E

Heathmap of the perception of issues related to the different PGBs.

	PGs relevance						PBs relevance					
	society perception	inadequate funding	conflicts of interest	land-use trade-offs	urban sprawling/ abandonment	land tenure/ access	society perception	inadequate funding	conflicts of interest	land-use trade-offs	urban sprawling/ abandonment	land tenure/ access
Productions quality and security (food, timber, energy)	42%	42%	35%	46%	46%	45%	42%	39%	38%	37%	42%	25%
Farmland biodiversity (animal and vegetal)	37%	46%	48%	49%	31%	21%	37%	45%	38%	32%	35%	18%
Resilience to Flooding, Landslides and Fire	39%	25%	46%	32%	23%	27%	28%	30%	28%	32%	18%	20%
Water Quality and availability	38%	23%	18%	11%	18%	10%	25%	23%	13%	10%	15%	13%
Air quality	38%	34%	30%	34%	35%	14%	31%	35%	30%	32%	18%	10%
Soil functionality	46%	30%	25%	28%	14%	10%	37%	30%	15%	20%	14%	14%
Climate stability	39%	28%	34%	37%	28%	20%	25%	20%	23%	20%	18%	14%
Landscape and scenery	31%	30%	28%	17%	56%	18%	24%	31%	27%	18%	41%	30%
Rural viability and vitality	25%	30%	34%	23%	15%	14%	20%	30%	14%	13%	15%	15%
Farm animal health and welfare	20%	23%	34%	13%	6%	10%	23%	27%	20%	8%	8%	8%

APPENDIX F

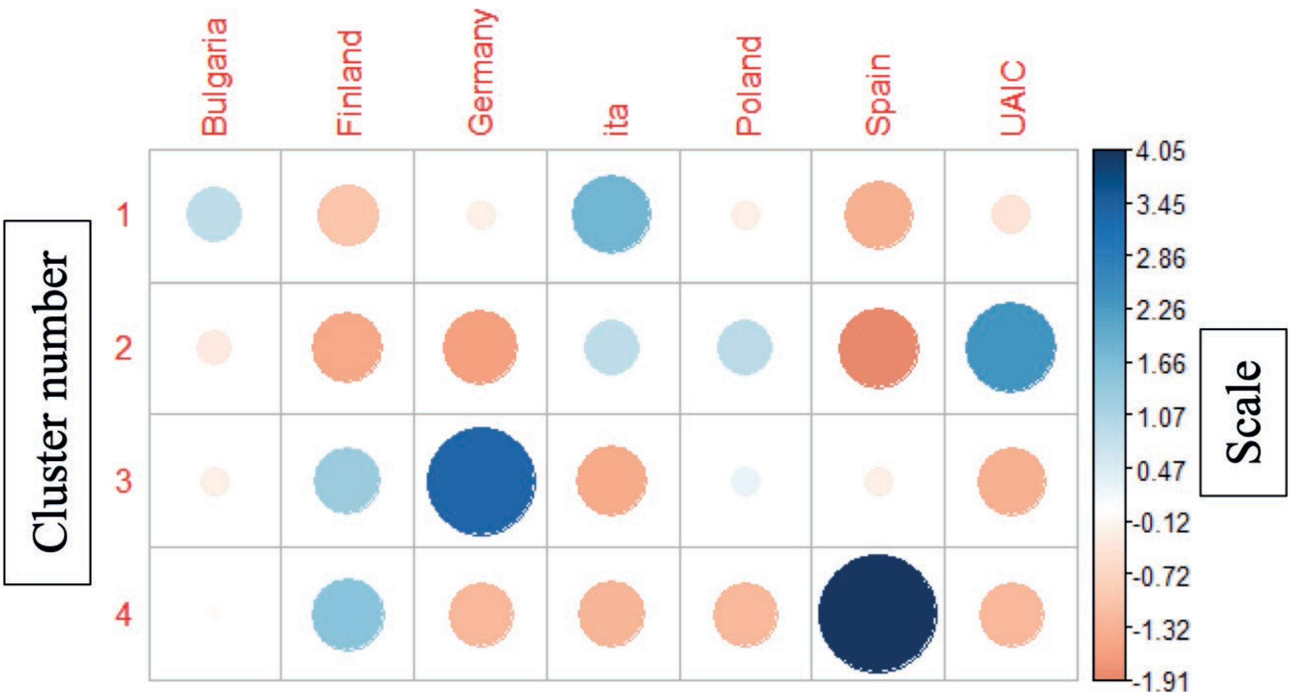
Heathmap of the perception of mechanisms able to foster PGs and reduce PBs.

	Fostering public goods						
	Increase financial support to farmers and foresters	Implement payments for environmental services (PES)	Implement new market-based incentives	Promote farmers' and foresters' education to sustainability	Adapt compensation schemes and regulations to the global market	Adopt more efficient land use plans	Pioneer/foster cross-compliance in all public subsidies
Production quality and security (food, timber, energy)	34%	23%	42%	38%	32%	23%	28%
Farmland biodiversity (animal and vegetal)	48%	59%	32%	42%	20%	37%	39%
Resilience to Flooding, Landslides and Fire	31%	35%	13%	45%	8%	28%	32%
Water Quality and availability	30%	49%	25%	42%	21%	37%	39%
Air quality	23%	30%	15%	35%	13%	23%	35%
Soil functionality	28%	48%	17%	46%	14%	45%	39%
Climate stability	28%	45%	17%	39%	25%	24%	34%
Landscape and scenery	38%	59%	24%	44%	10%	37%	41%
Rural viability and vitality	42%	24%	30%	30%	28%	31%	27%
Farm animal health and welfare	31%	31%	37%	38%	20%	20%	31%

	Reducing public bads						
	Increase financial support to farmers and foresters	Implement payments for environmental services (PES)	Implement new market-based incentives	Promote farmers' and foresters' education to sustainability	Adapt compensation schemes and regulations to the global market	Adopt more efficient land use plans	Pioneer cross-compliance in all public subsidies
Production quality and security (food, timber, energy)	32%	20%	38%	35%	28%	21%	24%
Farmland biodiversity (animal and vegetal)	46%	65%	37%	52%	20%	44%	51%
Resilience to Flooding, Landslides and Fire	23%	35%	15%	35%	14%	27%	28%
Water Quality and availability	35%	46%	28%	49%	15%	37%	46%
Air quality	24%	38%	15%	46%	14%	20%	37%
Soil functionality	31%	44%	17%	54%	13%	37%	42%
Climate stability	28%	44%	24%	48%	24%	30%	35%
Landscape and scenery	54%	46%	27%	46%	18%	42%	41%
Rural viability and vitality	37%	27%	20%	34%	18%	35%	24%
Farm animal health and welfare	30%	32%	42%	39%	27%	13%	37%

APPENDIX G

Correlogram outlining the relation between clusters and CSRs. The intensity of the blue colour is related to a positive relation, whereas red color indicates negative relations. The dimension of the bubble is proportional to the rate of the relation.



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The journal *Bio-based and Applied Economics* (*BAE*) provides a forum for presentation and discussion of applied research in the field of bio-based sectors and related policies, informing evidence-based decision-making and policy-making. It intends to provide a scholarly source of theoretical and applied studies while remaining widely accessible for non-researchers.

BAE seeks applied contributions on the economics of bio-based industries, such as agriculture, forestry, fishery and food, dealing with any related disciplines, such as resource and environmental economics, consumer studies, regional economics, innovation and development economics. Beside well-established fields of research related to these sectors, *BAE* aims in particular to explore cross-sectoral, recent and emerging themes characterizing the integrated management of biological resources, bio-based industries and sustainable development of rural areas. A special attention is also paid to the linkages between local and international dimensions. *BAE*'s objectives are:

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- to synthesize and integrate lessons learned from current strands of literature in economics;
- to provide a forum for well-established scholars as well as promising young researchers;
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