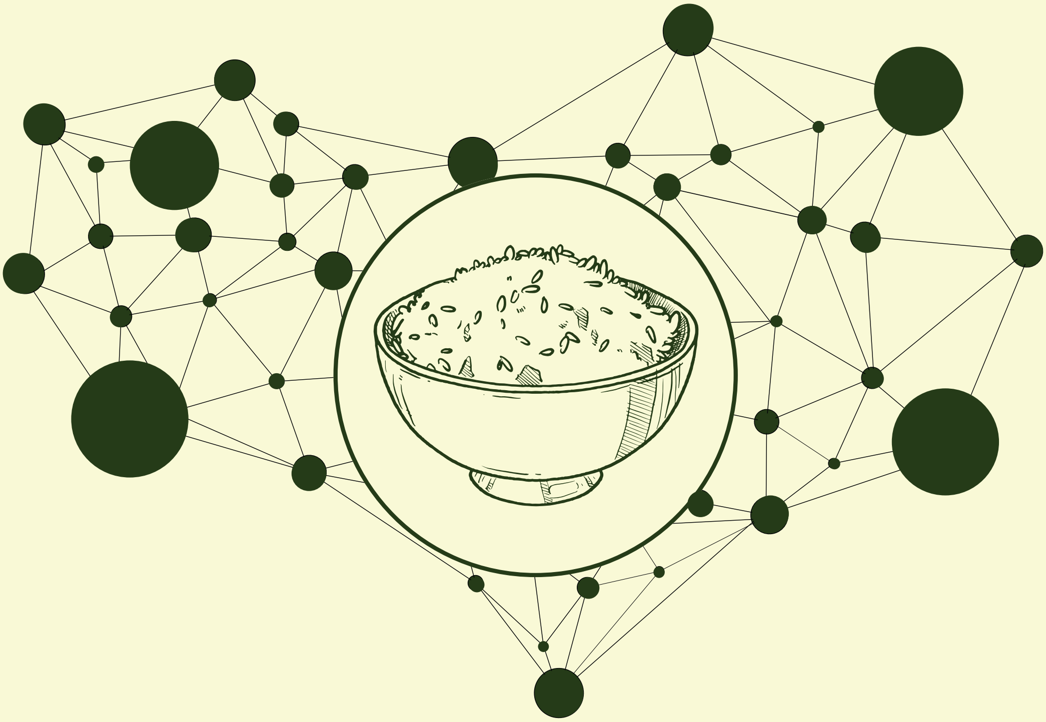
‘RICE TO SUSTAINABILITY’

A systems thinking approach to advance sustainable rice



Glory I. Edwards

Propositions

1. Rice sustainability is a moving target.
   (this thesis)

2. Food security and sustainability should go hand-in-hand to benefit people and nature.
   (this thesis)

3. Requesting interdisciplinary research in grant applications stimulates academic collaboration.

4. Documenting research failures produces scientific innovation.

5. Tax reductions and subsidies for environmentally harmful products and services should be abolished to stimulate sustainability transitions.

6. Multi-lateral Environmental Agreements (MEAs) perpetuate neo-colonialism.

Propositions belonging to the thesis, entitled

‘Rice to Sustainability’: A systems thinking approach to advance sustainable rice

Glory I. Edwards
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A systems thinking approach to advance sustainable rice

Glory I. Edwards

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Contents

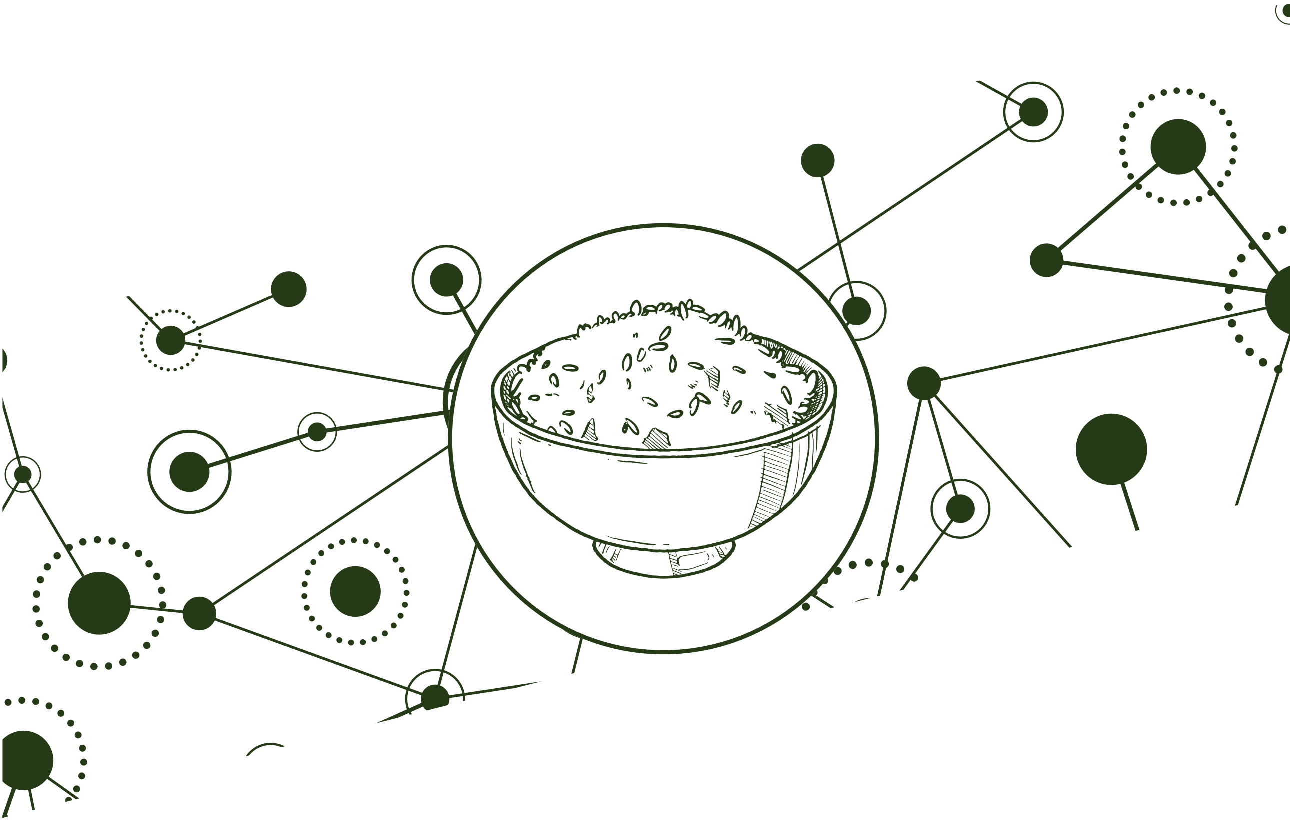
Chapter 1

Introduction

Sustainable Development Goal 2

"End hunger, achieve food security and improved nutrition and promote sustainable agriculture"

- UN General Assembly, Transforming our world: the 2030 Agenda for Sustainable Development, 21 October 2015, A/RES/70/1/14/35



1.1 The grand challenge of sustainable agriculture

Human activities push the Earth beyond its limits (Meadows et al. 1972), which are termed differently by different authors - the Earth's planetary boundaries (Rockström et al. 2009, Steffen et al. 2015), critical transitions (Scheffer et al. 2009), or tipping points (Lenton et al. 2008). These limits and associated boundary-crossing effects are characterised by biodiversity loss and changes in climate, freshwater and land use (Rockström et al. 2009). Agriculture is a key sector that strongly contributes to land-use and climate change taking the earth beyond sustainable limits (Campbell et al. 2017, Firbank et al. 2018, Conijn et al. 2018, Fischer 2018, Springmann et al. 2018). On the other hand, agriculture provides people with food, fibre and wood, and supports livelihoods through production, processing, distribution and consumption activities. Agriculture provides other ecosystem services such as biodiversity conservation, carbon sequestration and climate and water regulation (Thompson et al. 2007, Swinton et al. 2007, Schipanski et al. 2014). These services cut across social, economic and environmental contexts (Purvis et al. 2019), which, when combined, provide an integrated perspective on the dimensions and dynamics of agricultural production (Klapwijk et al. 2014).

Growing concerns over exceeding Earth's boundaries have promoted a shift towards sustainable agricultural production (Meadows et al. 1972, WCED 1987, Foley et al. 2005, World Bank Group 2007, Kiers et al. 2008, Rockström et al. 2009, Foley et al. 2011). Moreover, with increasing food demand, driven by an increasing and wealthier world population, improving the sustainability of agricultural production is more urgent than ever (Foley et al. 2011). The challenge of sustainable agricultural production is, for example, also stressed in the Paris Agreement, which states that food production should not be compromised while working towards climate-change adaptation, mitigation of greenhouse gas (GHG) emissions and resilience in agricultural and food systems (Article 2: UNFCCC, 2015).

The Sustainable Development Goals (SDGs), especially SDG 2, summon the global community to "end hunger, achieve food security and improve nutrition and promote sustainable agriculture" (FAO 2015). However, other SDGs are also closely tied to agricultural production. There are, therefore, multiple reasons and pressure to make agricultural production more sustainable. The challenge of achieving sustainability in agriculture is often called a 'wicked problem' in the context of the tensions between its many objectives, its nested and dynamic nature and its heterogeneity of scales (van Latesteijn and Rabbinge 2012, Dentoni and Ross 2013, Peters and Pierre 2014, Termeer et al. 2015, Kuhmonen 2018).

Sustainability is recognised as an integrative concept and process (Gibson 2006). The importance of integration has been consistently emphasized in various UN World Summit reports (UN 2002, UN 2012). However, despite its status as an integrative factor, achieving integration has proven challenging (Gibson, 2006). This is evident from the various attempts to advance the understanding of sustainability.

Conceptually, sustainability is often categorised into three dimensions - the social (society, people), the economic (economy, livelihoods) and the environmental (nature, planet) and sometimes expanded to include institutional, cultural and health aspects, represented as spheres or legs of sustainability (WCED 1987, Hancock 1993, Gibson 2006, Flint 2010). However, these spheres or legs approach overlooks the inherent interactions of these dimensions, treating them as separate entities (James and Magee 2016). Analytically, sustainability is addressed as parts of a whole but in practice, the notion of isolated spheres or legs of sustainability is flawed. Therefore a gap exists in understanding the interactions and interdependencies among dimensions of sustainability. In my thesis, I contribute to this need for integration by focusing on rice sustainability through a systems-thinking approach.

1.1.1 Rice systems

Rice production and consumption provide an excellent example of agriculture's multi-functional and multiple-scale nature that can help to understand sustainability transitions. Rice is produced in many different ways, in various ecosystems (upland, lowland and inland valleys), under different climatic conditions (tropical and sub-tropical), under different water regimes (in irrigated, partially irrigated and rainfed systems) with high inputs and low inputs (Zeigler and Barclay 2008, Dawe et al. 2010, Pandey et al. 2010).

In many cultures, rice is synonymous with food. In ancient Asian traditions, a meal without rice was not considered a meal (Anderson 1988). The ancient Chinese philosopher Confucius (Confucius 1809) regarded rice as the principal support of life and happiness: "*Coarse rice for food, water to drink and the bended arm for a pillow—happiness may be enjoyed even in these".* Rice's spiritual and cultural value of rice is well documented (Anderson 1988, Hamilton and Ammayao 2003). For centuries, farmers in the Mekong Delta have referred to rice as 'white gold', denoting their reliance on rice for wealth and well-being (Cramb 2020). Rice is also traditionally grown in parts of Africa, Northern Italy and North and South America (Pandey et al. 2010, Muthayya et al. 2014, van Oort et al. 2015, Van Ittersum et al. 2016).

Global rice consumption has increased in absolute values and in per capita consumption, although annual consumption varies substantially among countries ranging from 5 kg to 250 kg per person (FAOSTAT 2022). Increases in consumption were driven mainly by population growth in Asia, Latin America and Africa and by changing diets in Europe, Australia and North America (Fairhurst and Dobermann 2002). As a result, rice has become a major staple food. Aside from food supply, rice provides a range of other ecosystem services such as cultural identity, eco-tourism, climate regulation, flood-water control and water purification (Natuhara 2013, Settele et al. 2019).

From a resource-use perspective, modern-day rice production relies on land (Maclean et al. 2013) and irrigation water for up to a quarter of the global agricultural freshwater supply (Chapagain and Hoekstra 2011). In addition, paddy rice contributes about a tenth of global agricultural GHG emissions (Tubiello et al. 2013). However, rice production is also threatened by climate change impacts such as water scarcity, floods and sea level rise (Wassmann et al. 2009, Hatfield et al. 2011, Singh et al. 2017). As such, the livelihoods of millions of smallholder farmers with limited capacity to adapt to climate change (including extreme weather events) are at risk (Misra 2017, Nyadzi et al. 2019, Ojo and Baiyegunhi 2020, Ho et al. 2022).

Rice is nowadays important as a traded food commodity in local and international markets (Muthayya et al. 2014). The Green Revolution substantially increased rice yields, increasing many countries' ability to meet domestic needs and to sell surpluses on the international market (Borlaug 2007). Exporting rice in many developing countries is an important income source for farmers and a means for governments to earn foreign currencies and stimulate their economies.

However, the high per-capita rice consumption in major rice-producing countries and the concentration of exports in a few countries result in market volatility (Seck et al. 2012). This volatility has led to food crises, riots and panic during rice shortages (Zeigler and Barclay 2008, Dawe and Slayton 2012, Berazneva and Lee 2013). This underpins the importance of rice for global food security (Seck et al. 2012, Brooks and Place 2019). Food security will be further implicated due to projected increases in global rice demand and environmental changes (Wassmann et al. 2009, Timmer et al. 2010, Samal et al. 2022).

Multiple stakeholders are involved in rice production, distribution and consumption across different spatial scales. The biophysical aspects of rice cultivation are a factor to consider but need to be accompanied by an understanding the social, economic, institutional and cultural dimensions associated with rice from production to consumption.

1.1.2 Conceptual framework

Complexity is a core characteristic of many societal issues today and in this context, traditional, often linear methods fail (Meadows 2008). Well-intended research and interventions have been implemented but are often disciplinary and spatially and temporally fragmented (Foran et al. 2014, Eakin et al. 2017). Such fragmentation severely constrains sustainable agriculture (Béné et al. 2019, Davis et al. 2022). Integrating different bodies of knowledge and incorporating different dimensions, (i.e. the disciplinary, spatial and temporal dimensions) are necessary to achieve sustainability. Methodologies incorporating multiple dimensions are lacking, hindering detailed analysis.

In my thesis, I apply systems thinking as an integrative approach to assess these challenges. Systems thinking is a term for techniques, methods and skills that focus on understanding systems, their dimensions and interactions and predicting their dynamic behaviour interactions (including feedback and trade-offs) (Sterman 2000, Weinberg 2001, Ramage and Shipp 2012). A system here relates to a whole of interacting dimensions and their specific relationships that allow to identify entities with boundaries (Laszlo & Krippner, 1998). Systems thinking is generally used to conceptualise and model wicked problems, such as sustainability transitions and to evaluate possible solutions and their desired and unwanted consequences (Ramage and Shipp 2009, Arnold and Wade 2015).

A fundamental principle of systems thinking is that the behaviour of a system cannot be fully understood by studying its parts alone. Instead, it encourages a perspective in which the system's behaviour is determined by interactions (including feedbacks) between its parts and emergent properties. This approach allows for an in-depth understanding of a complex system by describing and understanding its structure and behaviour. Through this, opportunities for achieving desired outcomes, such as sustainability, can be identified (Wolstenholme 2003, Posthumus et al. 2018).

Systems thinking is applied widely in sustainability studies as it enables the planning and designing more sustainable systems (Liu et al. 2015, Zhang et al. 2018, Voulvoulis et al. 2022). For agricultural systems, systems thinking is likewise applied to organise different components across multiple dimensions (Allen and Hoekstra 1991, Posthumus et al. 2018, Zhang et al. 2018). Systems thinking also supports interdisciplinarity in agricultural practice (Bawden 1991, Schiere et al. 2004).

1.2 Research objective and questions

The objective of my thesis is to advance rice sustainability by applying a systems thinking approach. I aim to comprehensively understand the interactions and dynamics within rice systems and identify strategic interventions to enhance future sustainability across spatial and temporal scales.

This objective was achieved by addressing the following research questions (RQs):

RQ1: What national-level variations in key characteristics have shaped the historical and present sustainability of rice systems?

RQ2: What is the current structure, functioning and related dynamic behaviour of rice systems?

RQ3: What are the implications of future social, economic, environmental and institutional changes on the sustainability of rice systems?

RQ4: What pathways and strategies need to be established to ensure the sustainable development of rice systems?

1.3 Research methodology

I identified archetype analysis and scenario planning to address these RQs. Archetype and scenario analyses integrate spatial, temporal and disciplinary dimensions (Chermack 2004, Oteros-Rozas et al. 2015, Eisenack et al. 2019). I apply archetypes analysis for past to current temporal scale whereas scenario planning for future temporal scale. The following sub-sections will briefly introduce these techniques.

1.3.1 Archetype analysis

Archetypes are increasingly applied in sustainability research to complement system thinking by investigating recurrent patterns of system structure (Oberlack et al. 2019, Sietz et al. 2019). Archetypes are generalisations that identify patterns in cases or typologies of many cases. Archetypes are similar to syndromes which are patterns arising from human-nature interaction (Schellnhuber et al. 1997, Petschel-Held et al. 1999, Lüdeke et al. 2004). Archetypes are not restricted to identifying patterns and recurrent problematic system attributes but are also applied to identify solutions (Wolstenholme 2003, Lüdeke et al. 2004).

Archetypes analysis can be carried out as building blocks or by typologies. Archetypical building blocks allow for a case-based analysis by deducing a system's sustainability based on the expressions of already established generic patterns (Eisenack et al. 2019). Archetype analysis by typologies builds on the observation that complex systems exhibit classifiable recurrent patterns (Tittonell et al. 2020). Each case can be classified into a typology (e.g. Sietz et al. 2017, Václavík et al. 2013). Such analysis is inductive, by identifying similar patterns in a large number of cases (Eisenack et al. 2019) and can be done using indicator variables (Václavík et al. 2013), meta-analysis (Oberlack et al. 2016) or stakeholder engagement (Tittonell et al. 2020).

1.3.2 Scenario planning

Understanding the dynamics of complex systems is essential, but the inherent non-linearities and uncertainty of how such systems evolve are ignored in most decision-making contexts in planning for the future (Ogilvy 2002). Scenario planning considers systems' intrinsic complexity and unpredictability (Swart et al. 2004). Scenarios are plausible forms of the future based on a coherent and internally consistent set of assumptions about fundamental driving forces and relationships (Millennium Ecosystem Assessment 2003).

Scenario planning can serve two main goals: exploratory and normative (van Notten 2006, Börjeson et al. 2006, Höjer et al. 2008). Exploratory scenarios describe plausible alternative futures that evolve from current conditions and are influenced by socio-economic developments or environmental changes (van Notten 2006, O'Neill et al. 2014). Such scenarios represent changes under different 'what-if' questions (Börjeson et al. 2006).

On the other hand, normative scenarios describe a desired future and through backcasting assess what must be done to achieve such a future (Börjeson et al. 2006). Such an approach aims to build capacity and action towards this desired future. While exploratory scenarios investigate what could happen, normative scenarios provide plans for what should happen. Describing alternative futures or developing direction for desired futures improves understanding of plausible trends, consequences and (desired and undesired) potential outlooks.

1.4 Thesis chapters and methods applied

Achieving sustainability in rice systems requires the application of multiple research methods that combine insights from different disciplines. A systems thinking approach is a valuable starting point to understand and address complexities. In line with the systems thinking approach, I chose methods with an inherent systemic nature guided by a critical reflection on what is needed to achieve sustainability. Sustainability research essentially captures the dynamic changes that take place, comprehend their causes and consequences, provide means to influence or manage them and, ultimately, guide the transition towards a more desirable state of sustainability (Leemans 2016). These considerations can be condensed into three prerequisites for sustainability research - interactions, collaboration and foresight. In my thesis, I chose the most appropriate methods for each research chapter that consider the system's interactions and interdependencies, allow for diverse views of stakeholders to be considered through co-production and collaboration and evaluate future outcomes through foresight (Figure 1.1).

The methods enable the research of different components of rice systems. For archetype analysis, the methods are cluster analysis (Chapter 2) and fuzzy cognitive mapping (Chapters 3 and 4). These methods address past to present rice agricultural development worldwide, regionally and locally. Under scenario planning, I conduct land-use modelling for GHG emissions quantification (Chapter 5) and horizon scanning to identify research gaps for sustainability advancement (Chapter 6). The thesis applies in multidisciplinary way these individual research methods and together, as a methodological toolkit, the overall thesis is interdisciplinary (Figure 1.1). The interdisciplinary aspect entails the integration of diverse disciplines from the start of my thesis to address the properties of the system as well as emergent properties that result from systemic interactions. Conversely, transdisciplinarity emerges when multi-and interdisciplinary perspectives transcend their boundaries and converge to form a new integrated approach, often involving stakeholder participation (Bernstein 2015, Leavy 2016, Leemans and Fortuin 2023).

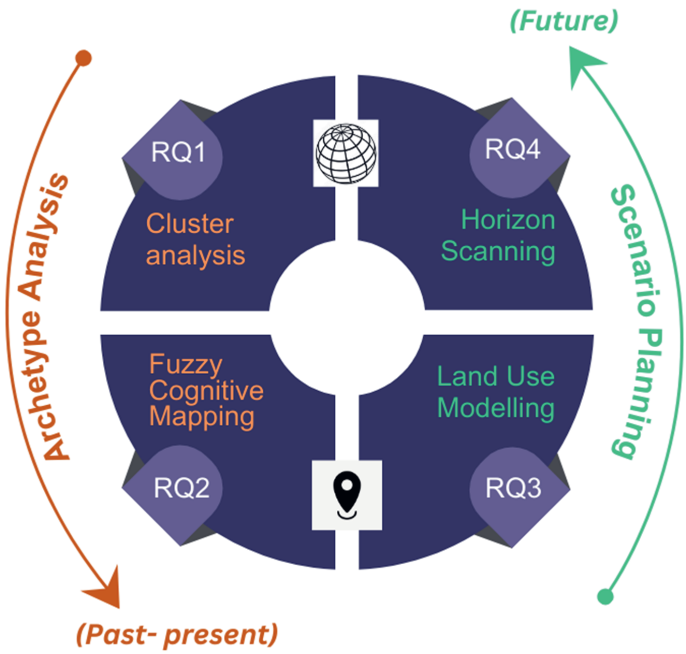


Figure 1.1 Overview of the thesis methods showing techniques – Archetype analysis and scenario planning broadly applied, matching the temporal scales. The methods in the wheel link to each of the research questions (RQs 1-4). The icons represent the global and local scale of the studies. Fuzzy cognitive mapping and land use modelling are local studies whereas cluster analysis and horizon scanning are global studies.

1.4.1 Chapter 2 – Cluster Analysis

In Chapter, an archetype analysis using self-organising maps, an automated clustering technique is conducted (Kohonen 2001, 2013). We apply archetype analysis as a comparative approach that reveals patterns across many heterogeneous cases (Magliocca et al. 2018, Oberlack et al. 2019).

Archetype analysis identifies distinct groups based on their characteristics and explains the mechanisms shaping the resulting archetypes (Oberlack et al. 2016, Sietz et al. 2017). The archetypes contain shared features between the units under study, for example, national food systems, allowing for more effective policy interventions and better coordination of global efforts towards achieving food security (Marshall et al. 2021). The resulting archetypes contain countries characterised by their similarity in factors. Further analysis with a time series, illustrates their specific variation in the short-term and long-term (RQ1).

1.4.2 Chapters 3 and 4 - Fuzzy cognitive mapping

In Chapters 3 and 4, the characteristics of Nigeria's rice system in its structure and system behaviour are uncovered through fuzzy cognitive mapping (RQ2). Chapter 3 reports on a participatory process to describe and analyse Nigeria's current rice agri-food system using fuzzy cognitive mapping. Stakeholders provide information on Nigeria's rice system, which I incorporated to build a fuzzy cognitive map which describes the system's structure and behaviour.

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In Chapter 4, I apply fuzzy cognitive maps as the archetypical building blocks (see Section 1.3.1). The feedback loop(s) in fuzzy cognitive maps, part of the system structure and behaviour, are matched with generic structural patterns, so-called system archetypes. System archetypes are often based on causal loop diagrams (Senge 1990, Wolstenholme 2003). Fuzzy cognitive maps are similar to causal loop diagrams using graph theory for qualitative system modelling (Voinov et al. 2018). I extend the basic causal loop diagram with fuzzy cognitive mapping by incorporating quantitative simulation to analyse the system behaviour. Furthermore, embedded in the system archetypes are strategies for moving the system to more desirable outcomes.

1.4.3 Chapter 5 - Land-use modelling using iCLUE

Chapter 5 quantifies Vietnam's national GHG emissions by 2050. Exploratory land-use scenarios are simulated in the Conversion of Land Use and its Effects model (iCLUE; Verweij et al. 2018). Land-use suitability is based on a statistical analysis of current land-use and drivers of the existing land use. The iCLUE model has two parts: a spatial analysis module and a non-spatial analysis module. The non-spatial analysis module focuses on factors influencing the spatial pattern of LULC change, such as socio-economic and regional spatial variables. The iCLUE model is spatially explicit and uses an inductive pattern for land distribution based on demand. In addition to the land use allocation, features such as GHG emissions quantification can be conducted in iCLUE by assigning emission intensities to each hectare of land. The spatial and temporal variation in emission intensities from rice fields and different land-use scenarios allow us to quantify the potential impacts of future changes on rice systems (RQ3).

1.4.4 Chapter 6 - Horizon scanning

Chapter 6 presents a horizon-scanning to identify research gaps for sustainable rice systems by 2050. The horizon scanning involves a global panel of rice experts in a two-round Delphi-style survey. Persistent and novel research gaps to achieve sustainable rice systems are discussed in this chapter.

Horizon scanning is another method applied in my thesis. Horizon scanning is a foresight activity to anticipate and plan for change (Cuhls 2020). Horizon scanning identifies novel ideas at the margins of current knowledge (Sutherland et al. 2019) and captures emerging trends with potential future impacts involving threats and opportunities (Esmail et al. 2020).

Horizon scanning is useful in engaging stakeholders in creating a desired future (Hideg et al. 2021). Additionally, research can be prioritised by funding agencies and policymakers using the outputs from a horizon scan (National Academies of Sciences 2020).

1.4.5 Chapter 7 – Synthesis

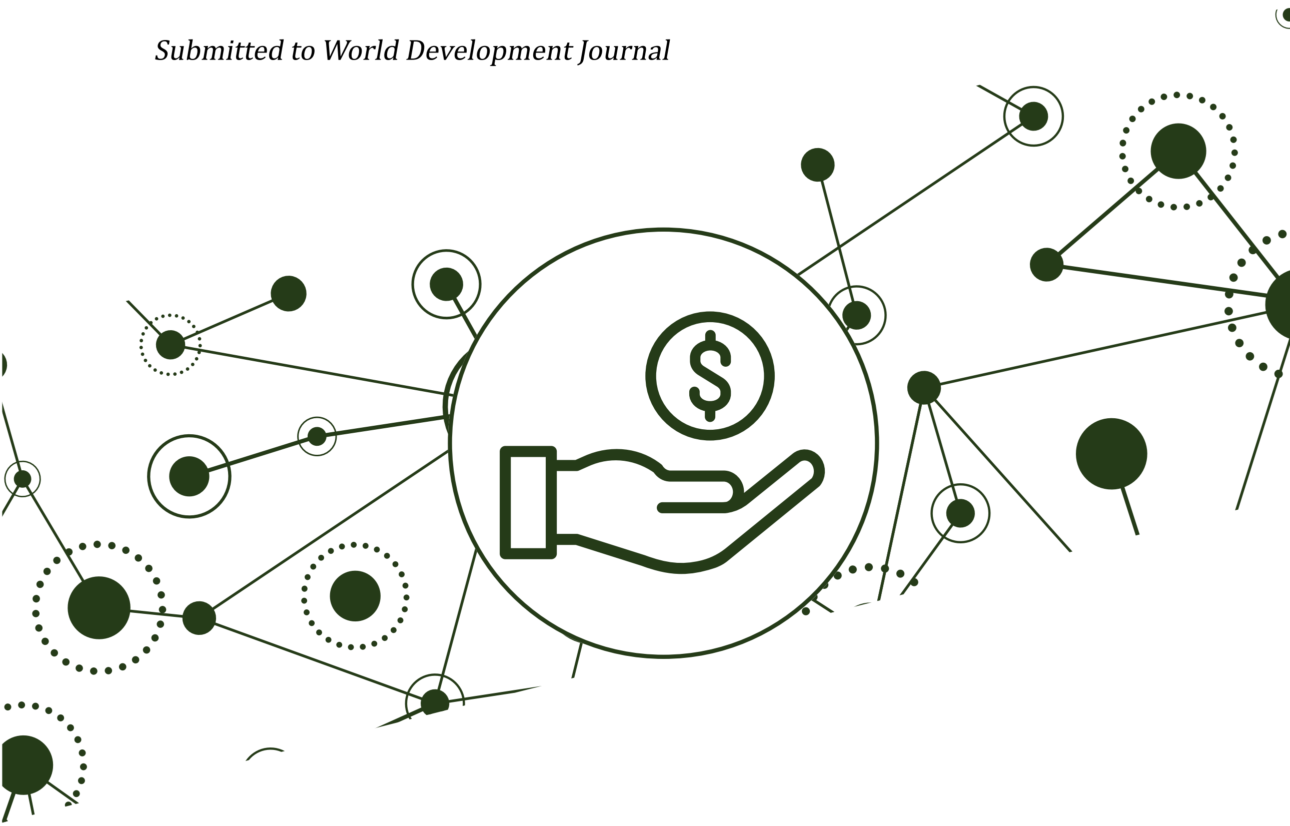
Chapters 2 to 6 of my thesis address the four RQs across the various spatial, temporal and disciplinary dimensions of rice systems (Figure 1.1). The methods together provide a practical systems-thinking approach that links past to present to future rice systems. The methods employed and the scales addressed allow for a transdisciplinary, integrative analysis to advance sustainability. The final chapter of my thesis (Chapter 7) summarises the main findings, reflects on the research methodology and integrates the results from each research chapter (Chapters 2-6). In Chapter 7, I synthesise the research findings into a system map, a visual description of rice systems that reflect the properties of the system and emergent properties that result from the systemic interactions aimed at advancing sustainability.

Chapter 2

Using archetype analysis to assess the resilience of rice systems to price spikes

Edwards G. I., Levers, C., Brusselaers, J., Mueller, D. & Kuemmerle, T. Using archetype analysis to assess the resilience of rice systems to price spikes.

Submitted to World Development Journal



Abstract

In an increasingly globalised world, socio-economic shocks such as economic recessions, pandemics, or wars can have far-reaching repercussions for food systems. Understanding the global resilience of countries to such shocks is therefore important, particularly for major grain crops that provide the bulk of staple food to global society. One important grain crop implicated in past food crises is rice, the key staple crop for half of the world's population. Here, we conduct an archetype analysis to understand the resilience of rice-producing countries to price spikes for the period 1961- 2019. First, we employ a cluster analysis based on self-organized maps using recent (2016-2019) data on rice production, suitable rice area extent, area equipped for irrigation, per capita rice consumption, import dependency and gross domestic product per capita. This yielded five coherent clusters of rice-producing countries with similar characteristics. Secondly, we analyse time series (1961-2019) and revealed trends in key explanatory factors that contribute to the resilience countries. The trends and patterns further characterised the clusters in five distinct archetypes that differ in their resilience to food price spikes: 'Laggards', 'Emergers', 'Grain and Water', 'Midfielders' and 'Thrivers'. The countries in the least resilient archetype (i.e. with high import dependency, low rice production capacity and low GDP per capita) are predominantly located in Africa and Asia . Countries in the more resilient archetypes have high and increasing GDP per capita and high yields. Our results detect and map major patterns in rice-producing countries and their potential resilience to price shocks. These results can inform policy-makers to design tailor-made interventions with respect to countries' resilience and allow for more effective and targeted coordination of global efforts towards achieving food security.

2.1 Introduction

In an increasingly globalised world, drastic socio-economic shocks can have far-reaching and major impacts on the global food systems (Puma et al. 2015, Bren d'Amour et al. 2016, Cottrell et al. 2019). The 2007-2008 global food price crisis marked a historic event when the international trading price of grains and other staple food commodities increased sharply. Rapid and large fluctuations in prices of food commodities leads to interruptions in food and nutrition security, particularly for low-income and net food-importing countries (Von Braun et al. 2008). Similar price spikes for staple food occurred in 1973-1974 and jeopardised food security. More recently, the COVID-19 pandemic in 2020 (Laborde et al. 2020) and the Russian invasion of Ukraine in 2022 led to trade disruptions that caused food price spikes (Hellegers 2022). Such socio-economic shocks are overall frequent and might become even more frequent in the future under adverse conditions such as climate change and conflict (Wheeler and von Braun 2013, Kuemmerle and Baumann 2021). At the same time, global food insecurity remains persistent despite global economic progress and given the rising population, will remain a challenge throughout the 21st century (von Grebmer et al. 2019).

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The causes of food price spikes are multiple and complex. They can, for example, result from declining world grain production caused by biophysical disruptions (Schnittker 1973). Similarly, market inefficiencies such as trade restrictions, panic buying, a general increase in commodity prices of energy and metals can play a role (Rosegrant et al. 2008, Childs and Kiawu 2009, Gilbert 2010). These past crises demonstrate that a broad set of causal factors can destabilise the global food system (Clapp 2023).

A food system that withstands such shock events by minimising food insecurity despite recurring disturbances is said to be resilient (Hoddinott 2014, Tendall et al. 2015, Schipanski et al. 2016). Food system resilience takes into account the current state of the system and how this state changes over time (Hoddinott 2014, Tendall et al. 2015, Schipanski et al. 2016). The properties that define resilience associate it with sustainability here defined as "development that meets the needs of the present generation without compromising the ability of future generations to meet their needs" (WCED, 1987) and food security (Béné et al. 2016, Schipanski et al. 2016, Meyer 2020, Béné 2020). Resilience thus encompasses the capacity of a system to withstand shocks and stresses as determined by its specific vulnerabilities (Zurek et al. 2022). As such, an understanding of resilience can improve food security and reduce vulnerabilities through better governance (Hoddinott 2023)

Shock events are caused by climate change, conflicts, pandemics and market disruptions leading to price spikes (de Steenhuijsen Piters et al. 2021, Kuemmerle and Baumann 2021). In this study we focus on price spikes as a potential shock to food systems. Our choice is informed from the pertinent impact of price spikes, causing recurrent food security challenges in a globalised world. Applying resilience thinking to food systems could thus help improve specific national food system resilience to global price spikes.

Previous studies have identified various factors that shape a countries' food system resilience to price spikes, e.g. the policy responses to past food shocks (Clapp and Moseley 2020), trade dependencies on other countries (Hellegers 2022), or the degree of price transmission from international prices to domestic prices (Robles 2013, Matters and Works 2014, Ceballos et al. 2016). Studies typically focus on the global food system (e.g. Puma et al. 2015, Marshall et al. 2021). But limited attention for national and regional contexts stifles food system transformation (Dengerink et al. 2021). Notably, some studies have focused on a region or selected countries or analysed national level data (e.g. Allen & Prosperi 2016, Moseley & Battersby 2020, Seekell et al. 2017). However, these studies are often not linked to specific food crops such as staple grain crops (rice, wheat, or maize), which jointly amount to almost half of the global calories consumed and which are the food crops mostly traded on the international markets. (Khoury et al. 2014, D'Odorico et al. 2014). Given that complexity of factors leading to food price spikes, especially for the staple grain crops, to increase the relevance of food system resilience studies, context-specific analysis must be conducted for the staple grain crops.

In this study, we focus on rice, an important staple food that feeds more than half of the world's population (Pandey et al. 2010), hence being critical for national and global food security (Seck et al. 2012). Among the major agricultural commodities (rice, corn, palm oil, soybeans, sugar, wheat), rice had the highest price spike during the 2007/08 price crisis, with rice prices tripling. This price spike was mainly triggered by the reliance of the international market on a few major exporters whose reactions in terms of export policies spiked global rice prices, rippling into other major food commodities such as wheat and corn (Childs and Kiawu 2009, Timmer 2010). Although rice prices have almost halved compared to their 2007-2008 highs, they have remained stable but well above pre-2007 levels, with implications for food security, human health and livelihoods sustenance (Clarete et al. 2013).

A promising approach to classify national rice systems according to their degree of resilience to rice price spikes is archetype analysis. Archetype analyses have emerged as a powerful set of concepts and analytical tools to analyse complex social-ecological phenomena with the goal to reach an intermediate level of complexity by identifying typical situations that can, by themselves be understood and explained (Oberlack et al. 2019). Archetype analysis is a comparative approach that reveals patterns across many heterogeneous cases (Magliocca et al. 2018, Oberlack et al. 2019). The methodology aims to identify distinct groups based on their characteristics and thus could be helpful to group countries that require similar attention and responses by policy-makers and stakeholders in the face of food price spikes.

Here, we use archetype analysis to assess the resilience of countries to global rice price spikes. The overarching research question in our study is "In what ways do countries exhibit variations in terms of the key characteristics that have shaped the historical and present resilience of food systems to rice price spikes?"

2.2 Methodology

2.2.1 Methodological framework

Archetype analysis has been carried out with empirical data using factors or indicators (Václavík et al. 2013, Kok et al. 2016) or meta-analysis of literature (Oberlack et al. 2016).

In our case, the archetype analysis consists of a two-step procedure taking into account aspects of time, space, causality etc. (Sietz et al. 2019).

The first step in our analysis was an analysis of the current state of systems by grouping countries using a cluster analysis. The cluster analysis serves to reduce the heterogeneity of the data. Subsequently, in the second step we conducted time series analysis on the derived clusters to better understand and explain the derived clusters by assessing the longer-term capacity and vulnerabilities of the rice systems within each cluster. An interpretation of both the short-term and the long-term country status of explanatory factors contribute to describing these clusters as archetypes of countries' resilience to rice price spikes (Figure 2.1).

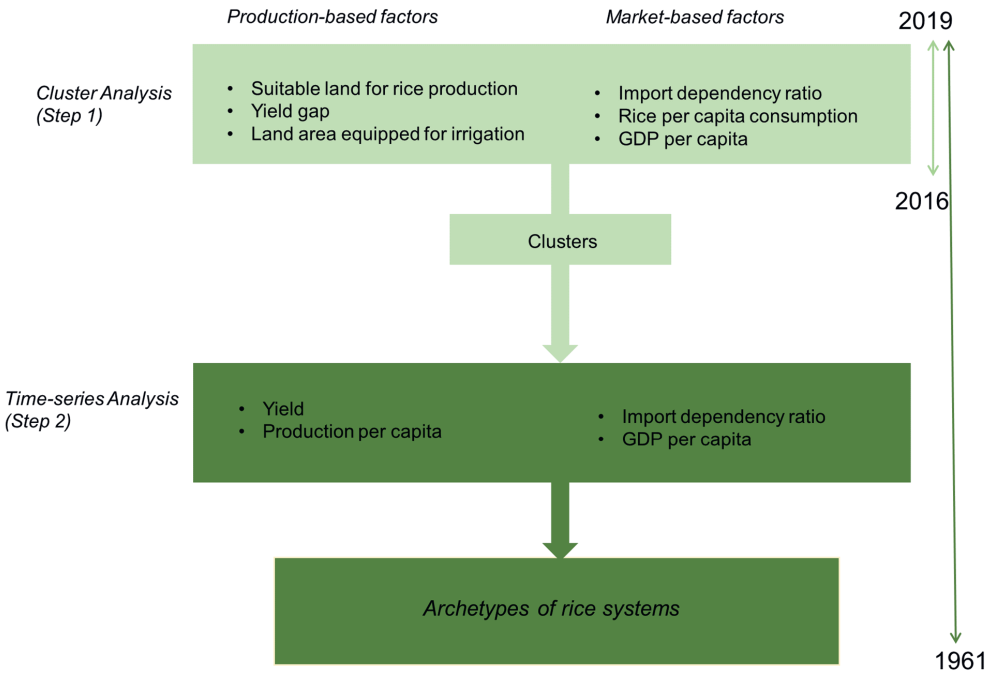

Figure 2.1 Methodological framework for deriving rice system archetypes by conducting a cluster analysis and a time series analysis.

STEP 1: Cluster Analysis

Clustering categorises and groups heterogeneous data to extract relevant patterns (Ştefan 2014). Many clustering algorithms exist, among which we use self-organising maps (SOM), based on Kohonen (2001, 2013). SOM reduces dimensional heterogeneity by extracting measures of similarity and dissimilarity from the input data (Das et al. 2016). These characteristics make SOM suitable for data-driven archetype analysis. To begin our analysis, we conducted the Hopkins test to check. to what extent the data allows for meaningful clustering of its objects. The value of the Hopkins statistic was above 0.7, which means the data is highly suitable for clustering and meaningful clusters can be derived from the data using clustering techniques.

2

The parameterisation of the SOMs requires determining the optimal number of clusters for the dataset to automate the generation of meaningful clusters. We determined the number of clusters using 26 different indices, including the *D* index, the Marriot index and the Rubin index from the *Nbclust* package (Charrad et al. 2014). Eleven out of 26 indices suggest an optimal number of 5 clusters (Supplementary material Figure SM2.1). The SOM model was trained from the input data for 100 iterations and the learning rate at 0.05 for the first 50 training iterations and then switched to 0.1 for the remaining iterations. We derived codebook vectors and used hierarchical clustering to further group the codebook vectors into the optimal number of clusters. To interpret the clusters, we calculated the arithmetic mean per cluster for all factors.

STEP 2- Time series analysis

To understand the capacity of a country's rice system over time, we analysed the temporal patterns within each cluster for key explanatory variables contributing to agricultural development– yield, per capita production and GDP per capita. Specifically, we measure the rate of change in these variables through a linear regression. The slope of a regression line (regression coefficient) represents the rate of change in the factor as time changes. The relative rate of change between time periods was further assessed using a rolling window regression, with the regression coefficient calculated in a 10-year window.

2.2.2 Datasets for analysis

For both steps of the archetype analysis, we considered data on production- and market-based factors. These factors are mostly rice-specific and constrained by available data at the national level. Our factor selection was also determined by correlation. We included in our analysis only factors with a correlation coefficient lower than 0.7 to prevent collinearity that can distort cluster results towards a single factor (Das and Chatterjee, 2011, Dormann et al. 2013).

We retrieved rice area and yield data from the FAOSTAT database (FAOSTAT 2022). Data on rice area, production and yield were available from FAOSTAT for 109 countries. 1961 was selected as the base year for the analysis since it is the earliest year when statistics on rice production were available in FAO databases. We eliminated countries with missing values and incomplete data sets for the period under analysis.

Import, export and GDP data were obtained from USDA Foreign Agricultural Service (USDA 2022). Data on the share of suitable rice area were retrieved from the Global Agro-Ecological Zoning version 4 (FAO and IIASA 2022) and data on harvested rice area from the Spatial Production Allocation Model (SPAM) (IFPRI (2019); Wood-Sichra et al. (2016); Supplementary material Table SM2.2). For imports and exports, we use the milled equivalent of rice paddy, because it is the milled product that is available for consumption after the rice husk and bran are removed (van Oort et al. 2015).

The final dataset was for 71 countries. The 71 countries account for 99% of total global rice production for 2016-2019. Hence the analysis is globally representative with 31% (n=71) from Africa, 30% from Asia, 17% from South America and the rest from other regions (Supplementary material Figure SM2.3). These factors are described in detail below and the datasets and sources have been made them available in the Supplementary material (Table SM2.2, Table SM2.5a-e).

The distribution of each factor is presented in Supplementary material (Figure SM2.4). The data for the suitable rice area share and yield gap have a symmetric distribution (skewness value near zero) whereas the other factors are all rightly skewed. Right-skewness indicates that the majority of the data are lower values. Only the share of suitable rice area and yield gap has almost asymmetrical data distribution showing even distribution around the means for the countries analysed.

Production-based factors

The production of rice is spread across different rice environments, climatic conditions and water regimes (Laborte et al. 2017; Pandey et al. 2010; Yuan et al. 2021). To allow comparisons between countries, we used generic production factors common to all countries.

- Suitable land for rice production: The production of rice is spread across different rice environments, climatic conditions and water regimes (Pandey et al. 2010, Laborte et al. 2017, Yuan et al. 2021). The share of suitable land for rice production reflects the country's biophysical and geographical suitability for individual crop types under specific input and management conditions. We calculated this factor as the share of the rice area extent assessed as 'very suitable' and 'suitable' from a total area extent assessed under all rice management types.
- Yield and yield gap: The increase in global rice production is more a result of a steady rise in global yield averages since the mid-20th century rather than rice area expansion (Ramankutty et al. 2018). Rice yields have more than tripled since 1961 but the rice area has only increased by 40%, indicating the relative importance of yield over production area in the increase in rice production (FAOSTAT 2022). Furthermore, the disparity between countries' yield levels remains the highest for rice yields compared to any other cereal crop underscoring the importance of understanding rice yield variation in addition to rice area (FAOSTAT 2022). The global variability in yield is best captured in the yield gap, which is the gap between the potential yield and the actual yield in a given location. Closing the yield gap is a relevant goal for policy development to meet the increased demand for rice (Foley et al. 2011, van Ittersum et al. 2013, van Oort et al. 2017). To calculate the yield gap, we used the attainable rice yield for wetland rice with high input from the GAEZ, which is the country's yield ceiling and calculated with the national average rice yield from FAOSTAT. We can determine

the potential to increase rice production within a country by closing the yield gap (van Ittersum et al. 2013). Yield and Yield gap are highly correlated variables so we use yield gap for the cluster analysis and yield for time series analysis.

- Area equipped for irrigation: Rice yields are strongly determined by irrigation which reduces reliance on rainfall and mitigates the effect of droughts (Dossou-Yovo et al. 2022). We used the factor - Land area equipped for irrigation as a percentage of agricultural area from the FAOSTAT database. Irrigation is a supply-push factor positively related to rice yield growth rates and, thus reflects a country's rice production capacity (Saito et al. 2015, van Oort et al. 2015).
- Production per capita: National rice supply comes from domestic rice production and rice imports. Fluctuations in rice imports contribute significantly to overall domestic rice supply variability, leading to food insecurity (Bren d'Amour and Anderson, 2020). The domestic rice production of a country must increase and reliance on rice imports reduce (Hoddinott 2023). We use the factor 'production per capita' which takes into account the population size of the country and allows for comparison between countries. Local production contributes to resilience of a country, especially in times of market disruptions (Seekell et al. 2017)

Market-based factors

Market-based factors are the social and economic factors that represent the assets and resources which increase a country's rice system resilience (Clarete et al. 2013). We also considered demographic conditions reflected in 'per capita' data on production, consumption and economic development.

- Import dependency ratio: Globalisation has led to highly connected food systems and so shocks likely spread across regions and sectors (Cottrell et al. 2019). Since the 1960s, rice has maintained ubiquity in national food supplies with a growth in the interdependencies of countries (Khoury et al. 2014). Thus, many countries depend on each other to meet their rice demands. The reliance on countries on each other has positive implications for increasing food supply where domestic production is low and for maximising production advantages in certain regions

(Porkka et al. 2017). However, import dependency limits resilience and food security of countries especially when reliance is on a few exporters (Kummu et al. 2020). Biophysical disruptions, local government policies Dependence also results from the trading of different types of rice. There are many types of rice, such as indica, aromatic, glutinous and japonica and the price quotations on the international markets vary for each rice type. The quality of rice varies and countries have different preferences for rice by type and quality. For example, Nigeria, one of Africa's largest rice importers, imports mainly milled, parboiled rice grain, whereas Liberia imports low-quality round-grained broken rice for making porridge (Rutsaert et al. 2013). Hence there is variation in the rice type being imported or exported and the prices for these different rice types. In our study to allow for a global comparison of countries, we treat rice as a uniform product and calculate import dependency as the ratio of subtracting the amount of imports from exports and then dividing it by the consumption quantity.

- Rice per capita consumption: The per capita rice consumption reflects the importance of rice in the country's diet (Benzie and John 2015). The higher the per capita consumption, the higher the diet homogeneity, which further predisposes a country to sharp fluctuations in rice prices (Khoury et al. 2014). Rice per capita consumption reflects reliance on rice for calories and is linked to household welfare and expenditure (Schmidt et al. 2021). Per capita production provides an insight into nutritional situation and relates to the capacity to adapt to a shock (Seekell et al. 2017).
- GDP per capita: In times of food price instability, a country can buffer the impacts of high prices by having a high Gross Domestic Product (GDP) (De Janvry and Sadoulet 2008, Mold 2011). GDP per capita thus indicates a country's ability to purchase rice from the international markets and coping capacity during food shocks (Lucas and Hilderink 2005, De Janvry and Sadoulet 2008). Countries with limited economic means to purchase sufficient food commodities are more vulnerable and can quickly become food deficient and experience higher levels of undernourishment during periods of high market prices. But when a country has

a high net food import dependence and low GDP, the poorer households are particularly susceptible to food insecurity, especially where the per capita rice consumption is high (Gustafson 2013). GDP per capita can also reflect the economic resources available to households which increase their resilience and capacity to cope or adapt to shocks (Béné et al. 2016). We use GDP per capita as an indicator of the agency and capacity for a people to develop strategies to counter price spikes as a shock event (Béné et al. 2016). As a strategy to price peaks and supply chain disruptions during the COVID-19 pandemic, purchasing power was found to influence household resilience much more than the health status (Béné 2020).

2.3 Results

Our analysis involved a 2-step process of cluster analysis and time series analysis. The results from both steps were combined to derive five archetypes, distinct representative groups within the data. The archetypes were assigned the labels – 'Laggards', 'Emergers', 'Mid-fielders', 'Grain and Water' and Thrivers. The archetypes are described below in the following sub-sections with their spatial patterns (from cluster analysis) and temporal patterns (from time series analysis).

2.3.1 Characteristics and spatial patterns

The archetypes differ in the range and mean values of factors used in the cluster analysis (Figure 2.2). The length of the bar represents the deviation from the average value for each factor. Archetype Laggards have the lowest area equipped for irrigation, lowest GDP per capita. The archetype with the highest area suitable for rice cultivation and the area equipped for irrigation is the Grain and Water Archetype. The Thrivers have the highest GDP per capita and lowest per capita consumption. Regarding the spatial patterns, the Archetypes Laggards and Emergers concentrate in Africa and Asia (Figure 2.3) whereas Thrivers are predominantly in Europe and South America.

2.3.2 Temporal changes from 1961-2019

We considered the rate of change of yield, per capita production and GDP per capita as indicators of the resilience of the rice system. All factors have upward trends (Figures 2.4 – 2.7) but with different regression coefficients in different time periods (Supplementary material Table SM 2.6).

Figure 2.2 Standardised mean values of factors for each archetype. The deviation from the average (zero) shows the relative differences between archetypes.

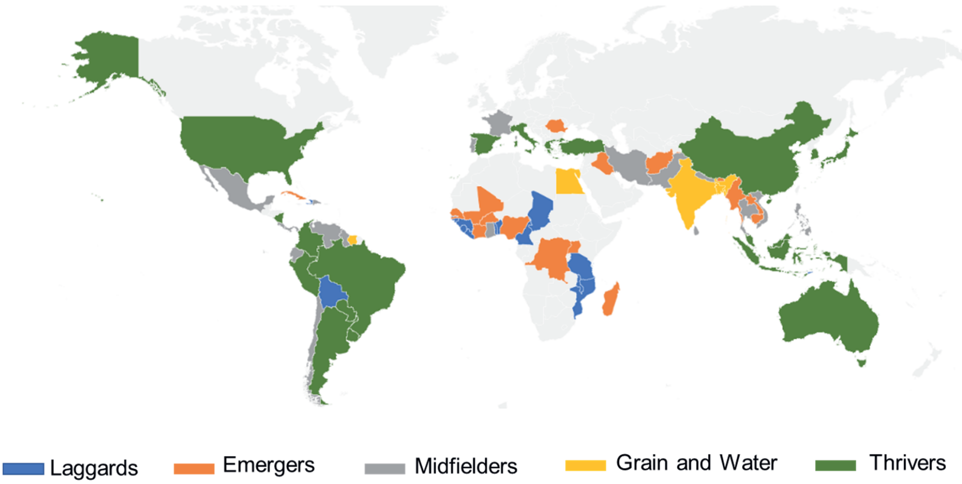

Figure 2.3: Geographic distribution of archetypes for 71 countries analysed

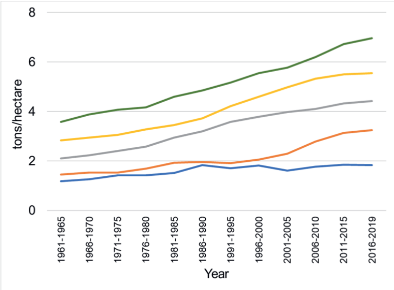

Figure 2.4 Time series trends in yield (tons/hectare)

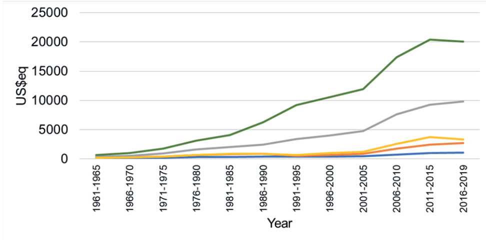

Figure 2.5 Time series trends in GDP per capita (US$ equivalent)

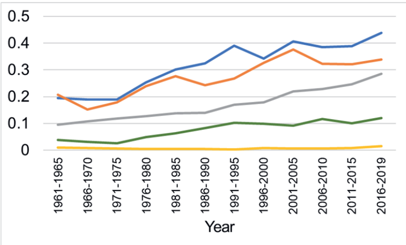

Figure 2.6 Time series trends in Import dependency ratio

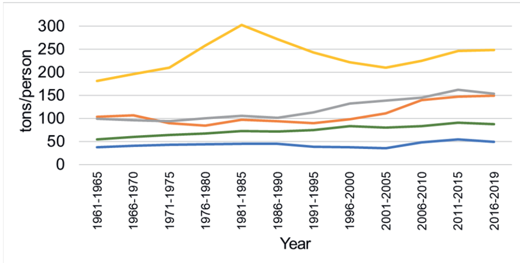

Figure 2.7 Time series trends in Production per capita (tons/person)

Laggards   Emergers   Midfielders   Grain and Water   Thrivers

2.3.3 Archetypes of Resilience of Rice Systems

Below, the cluster analysis results further analysed to detect patterns in their behaviour over time together provided insights into the degree of resilience of countries to rice price spikes resulting in 5 archetypes. We describe the 5 archetypes with their representative names, factor characteristics, geographic patterns and behaviour over time including their trend and variability.

Laggards: These countries have high yield gaps and import dependency. A third of these countries are lower-middle-income (Bolivia, Timor Leste, Benin, Cameroon and Tanzania), while the remainder are low-income countries. Yields have historically lagged for countries of this archetype compared to other archetypes (Figure 2.4). The weak growth in yields limits national rice production making these countries reliant on imports to meet their rice demand despite their relative low per capita consumption (Figure 2.4). Examples of countries in this archetype are Guinea and Bolivia (Figure 2.3).

Emergers: The countries belonging to this archetype have a slightly higher production capacity than Laggards archetype, as seen in the higher yields and area equipped for irrigation. Most of the countries are in Asia and Africa. There is an improvement in yields over time, comparably higher than in the Laggards archetype (Figure 2.4). At the start of the time period, the Emergers archetype had a higher import dependency ratio but at the end of the time period, the Emergers have lower import dependency ratio than the Laggards (Supplementary material Table SM2.6). The regression coefficient for production per capita shows an increase rate of change in production especially high in 2001-2010 period. The growth trajectory in rice production indicates an increasing resilience to global food crises (Supplementary material Table SM2.6). Countries in this Archetype include Nigeria and Senegal (Figure 2.3).

Midfielders: The countries in this archetype have a mid-range consumption and yield. They have higher area equipped for irrigation and GDP per capita relative to the previously described archetypes (Laggards and Emergers) (Figure 2.2). Countries in this archetype such as Guyana, Thailand and Vietnam have the highest rice production per capita and are major rice exporters in the world.

Grain and Water: The 'Grain and Water' archetype contain four countries with remarkably higher area equipped for irrigation than any other archetype (Figure 2.2). All four countries have consistently high production of rice per capita (Figure 2.7) and low import dependency ratio over the years (Figure 2.6). The archetype name 'Grain and Water' depicts the archetype's use of water from their extensive river systems to support the irrigation of their rice paddies.

Thrivers: Countries in this archetype show exceptional growth in rice yields over the 50 years from 1961 to 2019 (Figure 2.4). This archetype has the highest average GDP per capita and lowest yield gap (Figure 2.2). Countries in this archetype have low per capita rice consumption except for Indonesia and China. Even for these countries, reliance on external sources is low, reducing their overall resilience. The archetype Thrivers have the highest growth in GDP per capita (Figure 2.5) but in the last decade (2011-2019), the rate of change has dropped to be the lowest relative to other archetypes (Supplementary material Table SM2.6).

2.4 Discussion and Conclusions

We assessed countries' resilience to global rice food crises by considering various production- and market-based factors related to rice. We aimed to understand how countries vary regarding the key characteristics that have shaped the historical and present resilience to global rice crises.

2.4.1 Comparison of Resilience between Archetypes

Our study identified five archetypes of rice systems by their resilience to global rice food price spikes. The archetypes are the 'Laggards', 'Emergers', 'Midfielders', 'Grain and Water' and the 'Thrivers'. Resilience of archetypes results from their rice production capacities and other socio-economic factors increasing vulnerabilities to rice price spikes.

Our study has not defined specific cut off points, such as determining a minimum per capita consumption value or identifying the point at which import dependency becomes a risk. Rather we present the archetypes and compare them relative to each other emphasising the key vulnerabilities and capabilities that contribute to a country's resilience in the face of rice price spikes.

Many other factors are important for resilience such as health conditions, education as coping strategies (Hoddinott 2006), but since we focused on rice systems and rice price spikes, our factors for analysis are more closely related to rice to make the archetypes representative of the resilience conditions we aim to highlight in our study

Other studies confirmed the results we have obtained. For instance, Guinea is recognised as a country with the highest rise in reliance on rice (Elert 2014). In our study, Guinea is in the Laggards archetype which exhibited the steepest increase in reliance on rice (Figure 2.6).

The Laggards and Emergers archetypes with the highest import dependence and lowest GDP per capita fit the FAO classification of 'low-income food-deficit countries' (LIFDC) (FAO 2002). Until 1995, the FAO LIFDC classification referred to a food deficit that was a net trade deficit in cereals because cereals were the primary foods imported by low-income countries. LIFDCs are least resilient to unstable international prices and disrupted supply chains (Ivanic and Martin 2008).

These archetypes are concentrated in Africa and Asia (Figure 2.3) where most rice is produced and consumed globally (Elert 2014). The spatial patterns indicate a skewed global food system due to concentration of low resilience in regions, which has consequences for regional and global food security.

2.4.2 Policy Measures and Strategies

In the past, price spikes have had policy effects and responses such as the rise of rice self-sufficiency policies (van Oort et al. 2015, Clapp 2017, Arouna et al. 2020). Policy thus plays a role in increasing the resilience of rice systems before and after shock events (Hoddinott 2023). We assessed the resilience of countries, making our results useful for national-level policy-making.

National strategies can include production-based interventions through agricultural investments to increase domestic food production. We found that the archetypes with the highest import dependencies also exhibit lower yields, the lowest GDP per capita and area equipped for irrigation (Figure 2.2). These characteristics indicate places to intervene to increase countries’ production capacities and therefore, their reliance on external sources to meet their rice demand. Yield and irrigation infrastructure are points to intervene, especially for the Archetypes Laggards and Emergers which have made little progress in rice yields (Figure 2.4). This is also confirmed by other studies that link these two factors; for example, the yield gap can be reduced by expanding irrigated production areas (van Oort et al. 2015, Van Ittersum et al. 2016). Reducing yield gaps in these archetypes will increase rice production. Spatially, the archetypes are concentrated in Africa and Asia and many studies have emphasised that yield gaps need to be closed to increase rice production in Africa and the Asian countries lagging behind (Saito et al. 2015, van Oort et al. 2015, Yuan et al. 2022).

On the demand side, diversifying diets into other crops can reduce rice consumption and reliance on imports, counteracting the global diet homogeneity observed (Khoury et al. 2014). Another potential strategy is reducing consumer bias towards imported rice, as observed in West Africa (Demont 2013, Rutsaert et al. 2013). Value chain upgrading and protecting the local rice industry to keep local rice prices low reduces reliance on fragile international markets (Tondel et al. 2020, Soullier et al. 2020).

The Archetype 'Grain and water' boasts the highest area equipped for irrigation. These countries possess river systems to support the irrigation of their rice paddies. The Archetype 'Grain and Water' is resilient due to its potential for increasing rice production through irrigation infrastructure. However, other studies show that in current and future climate, the countries in Archetype 'Grain and Water' are particularly vulnerable to climate change impacts and weather variabilities such as the droughts, the El-Nino which affect rice production (Liu et al. 2014, Elbehri et al. 2015). Hence, adaptation to climate impact should be a target to maintain rice production. Cropping diversification is a strategy that can reduce production fluctuations and increase resilience in these countries (Savary et al. 2020, FAO 2021, Ammar 2022).

In addition to national strategies, regional collaborations will increase resilience to international shocks. Our results (Figure 2.3), along with other studies (e.g. Puma et al. 2015, Bren d'Amour et al. 2016), highlight the spatial clustering of countries with similar resilience, indicating that global food crises are likely to impact entire regions. Policy-makers in import-dependent countries should explore innovative solutions to decrease their reliance on distant exporting nations and instead strengthen their connections with neighbouring countries. For example, many West African countries meet some of their rice demand from their neighbours, reducing their resilience to cross-continental shocks and far distant exporting countries (Tondel et al. 2020, Arouna et al. 2020).

We have limited our analysis to only factors specific to rice and factors available for many countries for global analysis to be possible. We have not used other factors for lack of data or uncertainty in data. For example, we have not considered stocks in our analysis because the literature on stocks is controversial. While some studies suggest that stocks can buffer a country against price spikes (Bobenrieth et al. 2013, Hellegers 2022), others argue that stocks generate macroeconomic inefficiencies (Díaz-Bonilla 2017). For these reasons, we excluded stocks from our analysis to increase reproducibility of the study and applicability to rice systems. Understanding the resilience capacities of countries with contextual factors informs the design of appropriate and targeted policies (FAO 2021).

Although we have derived distinct archetypes, no one archetype is ranked more resilient than another. Our analysis particularly captured the variation between archetypes in their historical and present characteristics contributing to resilience to rice price spikes. Each archetype's vulnerabilities result from a combination of factors. By emphasising the specific characteristics related to each archetype, our research contributes to a better understanding of the key factors that have shaped the impact of food crises and the capacities of countries to maintain rice food security despite shock events and stresses. This knowledge is vital for policy-makers, researchers and organisations to develop effective strategies to mitigate the risks associated with global food crises. Agricultural research can be directed towards reducing countries' vulnerabilities and ensuring global food production and food security. Additionally, further policies and efforts by governments and international bodies towards global food security and world development should view rice system development as a process of change different across various spatial and temporal scales.

Chapter 3

Building a fuzzy cognitive map from stakeholder knowledge: An episodic, asynchronous approach

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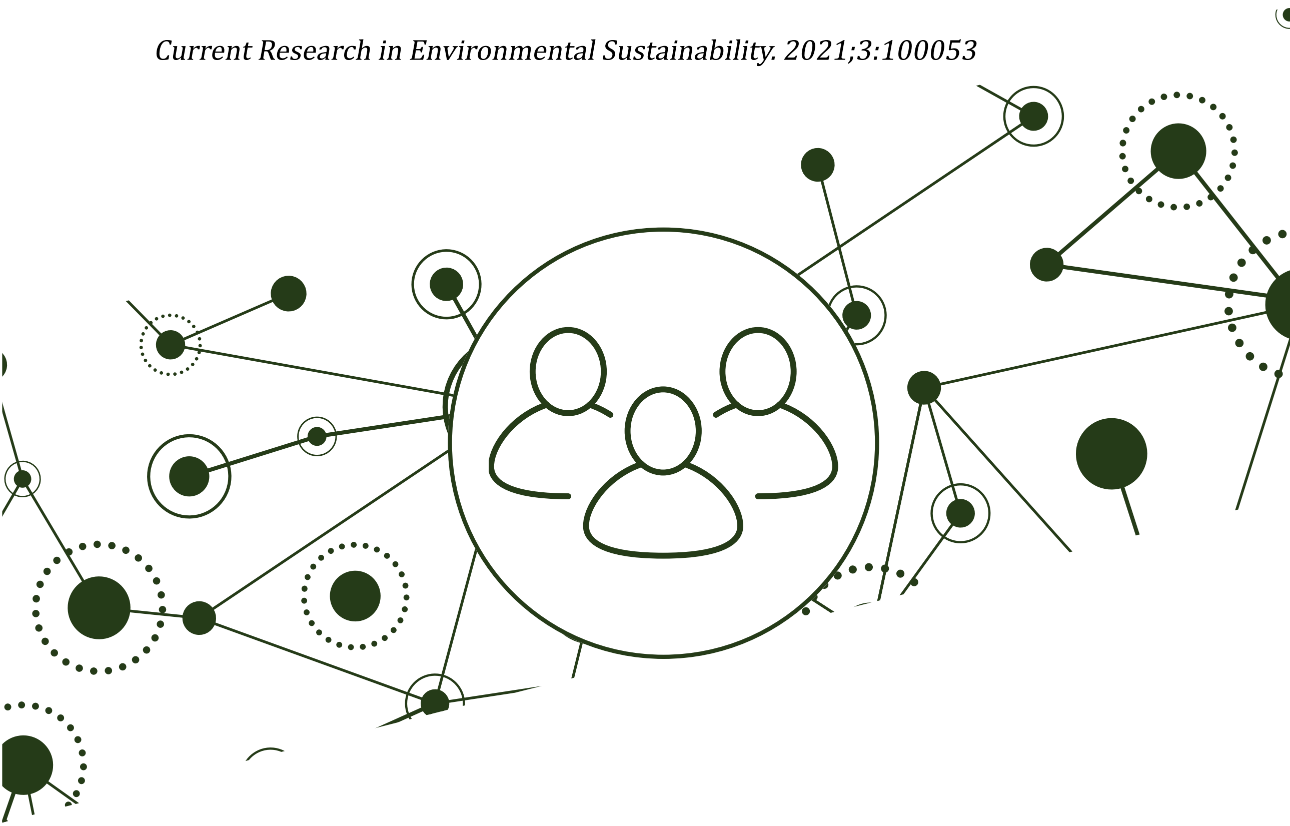


Abstract

Participatory modelling (PM) processes involve stakeholders in developing a simplified representation of reality based on stakeholders knowledge, perceptions, values and assumptions about a system in which they live and/or work. There has been an increase in the need for structured methods for the implementation of PM processes, to elicit knowledge from stakeholders and to represent this knowledge in a model. This paper presents a method to support the participatory component of modelling processes without the need for face-to-face interactions. The method, which we term Episodic and Asynchronous (EAsy) stakeholder participation is applied to develop a Fuzzy Cognitive Map of the Nigerian rice agri-food system. The results demonstrate that the EAsy approach is an effective way for co-production to be achieved without face-to-face interactions with stakeholders. The final output of this method yielded a stakeholder determined Fuzzy Cognitive Map of the system. The Fuzzy Cognitive Map was further applied in developing scenarios and identifying leverage points for intervention in the system. The EAsy approach can thus be considered valid to construct a representation of a complex social-ecological system. Using the results and analysis of our process, we discuss the limitations and benefits of the PM methodology.

3.1 Introduction

Many complex agricultural systems are characterised by factors that are not merely ecological but which also relate to social processes. Developing complete knowledge and understanding of such systems requires input from both scientists and stakeholders that are part of the system. This co-production integrates lay and scientific knowledge, using a diverse group of stakeholders to contribute towards understanding the system of interest in which they live and work (Voinov and Gaddis 2017). Using the valuable knowledge base of stakeholders, which is locally relevant and contextual, can increase the understanding of a system's dynamics and unravel complex system processes. Stakeholders participation also ensures an engagement with all those involved, fostering social learning and collective action towards desired goals, contributing to decision-making concerning a system (Butler and Adamowski 2015, Voinov and Gaddis 2017).

3.1.1 Choice of methods for Participatory Modelling

In participatory modelling (PM), input from stakeholders is incorporated in the form of their perceptions, values, opinions; into formalised and shared representation(s) of the system (Voinov et al. 2018). Several methods have been used in PM processes and there has been increased interest in these methods in recent years. Methods include concept mapping, causal loop diagrams, fuzzy cognitive mapping, scenario building, system dynamics, Bayesian networks, cellular automata, agent-based modelling, social multi-criteria evaluation (Munda 2004, Scholz et al. 2015, Le Page and Perrotton 2018, Olazabal et al. 2018, Büssing et al. 2019). These methods rely on graph theory, using cognitive thinking and social networks to describe complex and dynamic systems (Yoon and Jetter 2016). In this wide range of tools/methods, co-production occurs when stakeholders are involved at one or more stages of the modelling process. The involvement of stakeholders' knowledge and values follows the extended science perspective and the post-normal construct for complex systems characterised by uncertainties (Funtowicz and Ravetz 1994, Munda 2004, Bremer and Meisch 2017).

Recent studies have guided the selection of methods for a PM process. First and foremost, the purpose of the PM should be considered (Kelly et al. 2013, Gramberger et al. 2015, Voinov et al. 2018). PM is embarked upon with different purposes in mind: to achieve social objectives such as mutual learning, communication and problem-solving; to describe and enhance understanding of a system; or to predict what might happen in the future; and also to support decision-making policymaking and management of a system (Gray et al. 2018, Voinov et al. 2018). When the purpose of the PM is clear, it can be decided how and when to involve stakeholders in the process.

Secondly, the choice of method should be guided by how easily the method will allow for diverse groups of stakeholders to be involved (Voinov et al. 2018). Stakeholders' resource constraints, technical ability and capacity to use and continue with a particular tool should be considered (Diniz et al. 2015). A wrong choice of methods can lead to the exclusion of groups whose knowledge should be represented in the model (Fairweather 2010, Denney et al. 2018).

A third consideration for choosing a method is bridging the gap between a qualitative phase of the PM process and a quantitative phase of mathematical modelling. The ease with which stakeholder-derived knowledge, which is often qualitative can be converted to quantitative data to be used in a model should be considered, as well as the use of visualisations to communicate model outputs (Voinov et al. 2018).

3.1.2 Realising Stakeholder participation in Participatory Modelling

Stakeholder participation in a given PM method can be realised in various ways. Figure 3.1 shows different methods of participation according to the characteristics of the process in space and time. Co-production efforts in PM can be deployed in face-to-face settings, where a group of stakeholders meet in one place and at the same time. Workshops, forums and group modelling processes fall under this category (Quadrant 1 of Figure 3.1). In Quadrant 3, stakeholders are consulted to provide feedback, usually as a way to validate a product. In this case, stakeholders are in different places and not brought together in one location to provide this feedback. Such inclusion of stakeholders who are at different times and places is termed asynchronous participation (Pahl-Wostl 2008).

In the type of approach mentioned in Quadrant 4, inputs from a wide range of stakeholders groups are collected at different times and locations (asynchronous) over different short intervals of the process (episodic). While the original representation by Pahl-Wostl (2008) refers to consultation over the internet in Quadrant 4, many other methods could be included here. Individual interviews which are done over the telephone, completing online forms, use of self-administered surveys or web applications are all asynchronous modes of participation (Voinov et al. 2016, Gray et al. 2018).

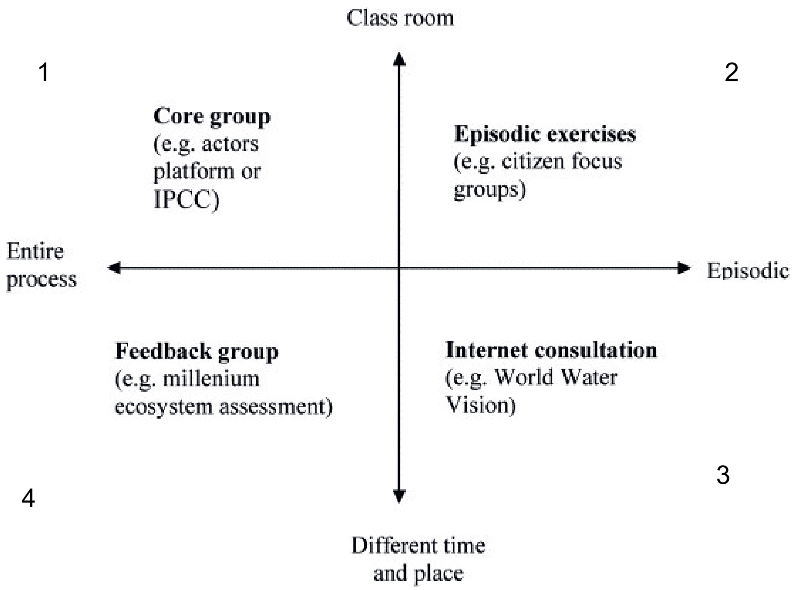


Figure 3.1: Matrix for the categorisation of participation and methods according to the characteristics of the process in time and space (Pahl-Wostl 2008).

With the advent of technology, a host of online techniques and new media offer different and possibly more effective ways to support the participatory component of modelling processes without the need for face-to-face interactions (Kolagani and Ramu 2017, Afzalan and Muller 2018, Voinov et al. 2018). These online techniques use asynchronous participation and offer solutions to the challenges of implementing face-to-face PM

3

settings. Challenges such as logistical constraints of gathering people in one place at the same time, time and resource constraints in arranging meetings and the need for managing group dynamics in group modelling settings (Diniz et al. 2015, Gramberger et al. 2015, Denney et al. 2018).

3.1.3 Objectives

To ensure the implementation of PM processes, structured methods proposing good practices and detailed step-by-step methodologies have been a research target (Gray et al. 2018). Structured methods allow for standardised reporting, increasing transparency and reproducibility at every stage of a PM process (Gray et al. 2018, Olazabal et al. 2018). In this paper, we propose a structured method for asynchronous participation of stakeholders in PM. Structured methods ensure that the PM process achieves its aims; the products represent stakeholder input on their knowledge of the system without tipping the balance of co-production to the researchers. This method is both episodic and asynchronous, involving two episodes of stakeholder engagement without face-to-face interactions or visual means of engaging with the stakeholders.

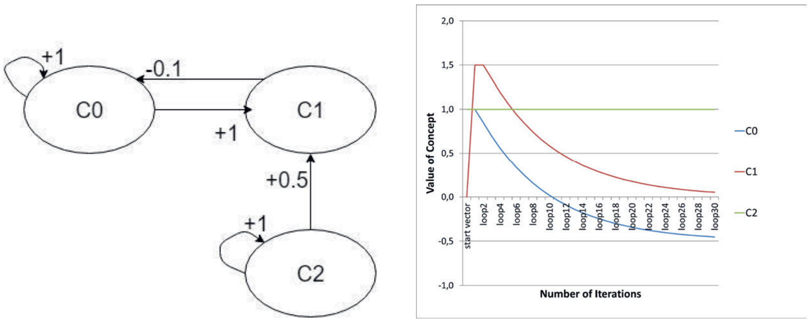
We apply the proposed method which we refer to as Episodic and Asynchronous (EAsy) to develop a Fuzzy Cognitive Map (FCM) of the current rice agri-food system of Nigeria using stakeholder knowledge. In the rest of this chapter, we show a concrete method with standardised reporting, to increase transparency and reproducibility of the method. We discuss the benefits and drawbacks of this approach and the related challenges that this approach could address in PM processes. The central focus of this paper is on the PM methodology with a complementary paper (Chapter 4 of this thesis, also Edwards et al. 2023) elaborating on the results.

3.2 Background of Study

3.2.1 Fuzzy Cognitive Mapping (FCM)

Fuzzy cognitive map(ping) (FCM) is a technique that builds quasi-quantitative models from the knowledge of interconnected variables in a system (Jetter and Kok 2014). FCM is suitable for linking stakeholders' knowledge and scientific knowledge in modelling a complex social-ecological system and has been praised for the ease and speed of obtaining and combining different knowledge sources (Kok 2009, Jetter and Kok 2014, Alizadeh and Jetter 2017, Voinov et al. 2018).

An FCM represents the variables of a system as 'concepts' and assesses the strength between these concepts as causal 'connections' represented by arrows with positive (+) or negative (-) values between -1 and 1 (Figure 3.2a). The particular strength of FCM is that it can be used to analyse the quasi-dynamic behaviour of the system derived by multiplying the FCM's weight matrix by the state vector (Figure 3.2b). A wealth of scientific literature offers further details on the structure and functioning of FCMs. For example, Gray et al. (2018), Diniz et al. (2015), Papageorgiou and Salmeron (2013), Kok (2009).



(a) (b)

Figure 3.2: An example of a Fuzzy Cognitive Map (a) a directed graph, showing concepts, C1, C2, C3 linked by weighted connections (arrows with positive or negative values) (b) showing a dynamic graph, number of iterations by the value of concepts (Kok 2009)

FCMs are useful in modelling complex social-ecological systems as perceived by the stakeholders living and working in the system (Voinov and Gaddis 2017). The nature of an FCM makes it easy for stakeholders to participate in the diagramming of the map or contribute knowledge for the map building individually or as a group. FCMs are particularly flexible in allowing the inclusion of both quantifiable and difficult to quantify aspects of a complex system and the different domains of the system (Kafetzis et al. 2010).

Crucial steps in the development methods of an FCM include the data collection in PM settings: knowledge elicitation from stakeholders; knowledge analysis and FCM aggregation. These will all receive ample attention in the application presented here.

3.2.2 Case Study: Rice agri-food system in Nigeria

A demonstration of the method we discuss in this chapter is provided using a case study of the rice agri-food system in Nigeria. FCMs have been used in similar studies to elicit and represent knowledge of a complex agricultural and social-ecological system (Fairweather 2010, Halbrendt et al. 2014, Bardenhagen et al. 2020). The case study is at the national level and approaches the rice system from production to consumption.

Rice, a staple food for half of the world's population, is designated as one of the ten crops that feed the world, especially feeding consumers in Asia and Africa (Seck et al. 2012). In Africa, rice is an all-important crop for food security and foreign exchange and indirectly, for example, for gender equality and youth employment. Annual rice consumption has more than doubled and continues to increase rapidly in most African countries, caused by high population growth rates and changing consumer preferences (Maclean et al. 2013).

Over the last decade, Nigeria has become the second-largest producer of rice in Africa, yet at the same time; rice consumption has greatly increased, necessitating rice import to close the gap between production and consumption (P/C ratio) (Obayelu 2015, van Oort et al. 2015). It is projected that Nigeria will become the third most populous country in the world by 2050, which will further increase rice demand (Seck et al. 2012, Riahi et al. 2017). The Federal Government of Nigeria has made rice food security a major policy priority, intending to achieve rice self-sufficiency (P/C ratio ≥ 1). This is implemented through programmes such as the Agriculture Promotion Policy (APP) (2016-2020) and Economic Recovery and Growth Plan (ERGP) (2017-2020), which proposed to increase domestic rice production and improve its competitiveness with imports by employing a combination of trade policies (import tariffs and bans), input subsidising and other direct investments along the rice value chain (Sule et al. 2019).

Despite these policy efforts, rice food demand is far from met. The complexity of the rice agri-food system, with multiple interactions between human and natural components, poses a major challenge for the Government and stakeholders to actualise rice food security. Achieving rice food security and the Government's goal of self-sufficiency requires a systems analysis. For a system fraught with uncertainties and instabilities, a systems analysis will enhance the current understanding of the system and allow to explore of future scenarios and pathways (Arnold and Wade 2015, Zhang et al. 2018).

3.3 Methodology

Figure 3.3 shows the step-wise approach, process and intermediate products of the methodology that were followed. Our approach follows guidelines by Olazabal et al. (2018) for FCM based on individual interviews and Alizadeh and Jetter (2017) on using secondary sources to augment stakeholders' knowledge. The methodology includes two episodes of stakeholder engagement, first through telephone interviews (Step 3) and secondly, through online forms (Step 5). In Step 4, knowledge from stakeholders is analysed and aggregated qualitatively. In Step 5, stakeholders provide qualitative weightings to connections. In Step 6, the qualitative weightings are converted into quantitative values.

The process has a funnel shape design (Figure 3.3). Beginning with broad steps of defining the study's objective to stakeholder selection to eliciting knowledge from stakeholders (Steps 1 -3), narrowing stakeholder knowledge by grouping similar concepts under generalised labels (Step 4). Further narrowing occurs as established connections are presented to stakeholders to be weighted (Step 5). These weights are aggregated to make the final FCM - a single representation of stakeholder knowledge of the system (Step 6). The step-wise process is explained in the next sections.

3.3.1 STEP 1: Definition of Objective and Scope

FCM development begins with defining the objective and the scope of the study. The objective and the scope both guide stakeholder identification and guide the questions posed to stakeholders to elicit knowledge of the system. The scope refers to the study area the FCM aims to describe. Delineating the scope is important as discussions at different levels yield different results. For instance, describing a system at the farm level will yield other concepts from describing a system on a larger level such as the national level.

The objective of FCM development for this study was to understand and map the rice agri-food system and the scope was at the national level in Nigeria. The central issue discussed was the drivers of rice production in Nigeria. As such, rice production became the central concept and the beginning of FCM diagramming.

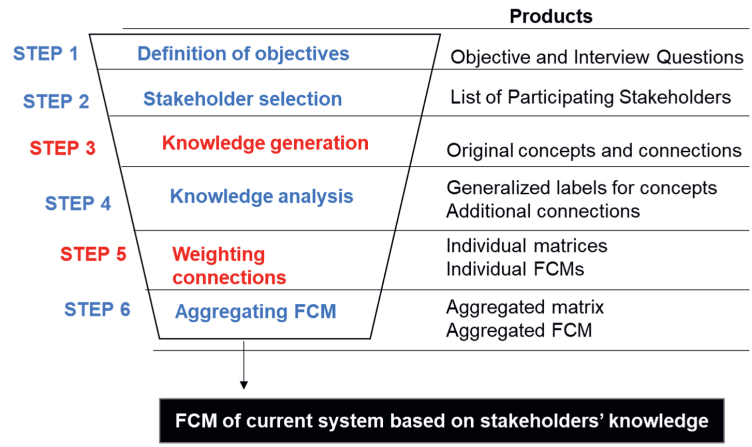


Figure 3.3: Fuzzy Cognitive Map building steps and products. The steps in red represent stakeholder participation steps, while the steps in blue are researcher-led.

3.3.2 STEP 2: Stakeholder Selection

Integrating multiple perspectives in understanding a complex system is highly dependent on the participating stakeholders, which makes stakeholder selection very important. Stakeholder selection was based broadly on the Prospex-CQI method.

Criteria (C): Defining a set of criteria and categories for stakeholder groups that are either affecting or affected by the system

Quota (Q): Setting a specific minimum quota for all categories

Individuals (I): Identifying individuals that fit the categories, with the overall selection fitting the quotas set (Gramberger et al. 2015).

Following these criteria, in this study, four categories were present - academia, research institute staff, farmers, government agencies etc. We began by contacting stakeholders affiliated with institutions and then within each stakeholder category, other individuals were reached using snowballing. Participating stakeholders consisted of multi-actor and multi-scale set of stakeholders.

3.3.3 STEP 3: Knowledge Generation

Stakeholder involvement alone is not enough to satisfy that a PM process took place. It is necessary to ensure that stakeholder knowledge is elicited, analysed and represented in the intermediate and final products of the PM (Olazabal et al. 2018). The researcher is tasked with designing and executing the stakeholder engagement during the PM process. The role of the researcher becomes crucial as it determines the balance of co-production, regulating how much stakeholder input versus the researcher's input is used in the process.

We had semi-structured interviews separately with each individual over the telephone. The same interviewer conducted all the interviews to reduce bias and risks of losing important knowledge. Stakeholders were asked to respond to the questions according to their perception, experience and/or expertise. Interview sessions ranged from 30 to 90 minutes in duration. All the interviews were conducted within three months.

At the start of the interview, the study's objective and scope were explained to the stakeholder. Stakeholders were briefed to consider as wide a range as possible of concepts/factors/drivers including social, economic and environmental factors influencing rice production. The stakeholders were asked to describe the relationships and connections between concepts and rice production (central concept). No predefined list of concepts was provided for stakeholders. The interview questions (Supplementary material Table SM3.1) served as a guide to navigate the interview. Depending on the stakeholder's response, follow-up questions were asked to obtain more detail while keeping rice production the central focus of the interview.

3.3.4 STEP 4: Qualitative aggregation

In this step, we collated a list of concepts mentioned in all stakeholder interviews. We further analysed these concepts by clustering similar concepts/terms together. To support this aggregation, we conducted a content analysis of scientific publications in the field of rice that refer to the case study country, Nigeria. It is good practice to consider stakeholder knowledge together with scientific knowledge when aggregating stakeholders' knowledge. This ensures the internal consistency of the model and validates the model with empirically established relationships(Hobbs et al. 2002, Özesmi and Özesmi 2004).

Thereafter, we analysed the statements made by stakeholders one after the other to establish connections. For example, stakeholder A3 made the statement: "there is an increase in local demand and this serves as a stimulus for rice farmers to produce rice due to unavailability of competing alternatives". The above statement directly converts to Figure 3.4a. The statement gives the reason for the increase in demand for local rice as 'unavailability of competing alternatives'. The root cause for the unavailability of competing alternatives is the government policies on rice import bans. So we link this concept to the 'increase in demand for local rice' (Figure 3.4b).

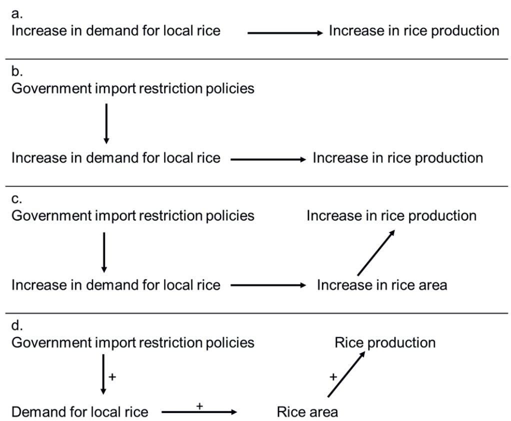


Figure 3.4 (a-d) Conversion of a statement to part of the fuzzy cognitive map - "there is an increase in local demand and this serves as a stimulus for rice farmers to produce rice due to unavailability of competing alternatives".

Increases in the (total) rice production are attributed to both an increase in the rice production area (hectare) and increased productivity of rice production (yield/hectare). Consequently, the only concepts that directly influence total rice production are expansion in the rice production area and an increase in rice productivity. From the interviews, many stakeholders do not mention these sub-connections but rather link concepts directly to rice production. Here, the need arises for the researcher to granulate and augment concepts and connections (Alizadeh and Jetter 2017). In our study, the content analysis of literature provided the commonly used terms in literature. For the statement under analysis, the concept rice area connects to rice production. Therefore, the connections are expanded to give Figure 3.4c.

This process needs to be repeated by revisiting statements and checking the logic and internal consistency within the concepts and connections. We worked through all the initial concepts and connections provided by stakeholders during the interviews. We removed the terms 'increase' or 'decrease' and attached signs (positive or negative) to each connection. For the statement under analysis, the connections in Figure 3.4d results.

3.3.5 STEP 5: Weighting connections

Stakeholders participated in a 2nd episode by completing an online form. Stakeholders are presented with connections as pairwise relationships. FCMs can be considered representations of pairwise associations using qualitative terms which we convert to quantitatively assigned weighted edges between -1 and 1. These pairwise relationships allow computation of the cumulative strength of connections between the concepts with weighted edges, highlighting these connections as a system (Gray et al. 2015).

Stakeholders were asked to choose from the qualitative values – strong, medium and weak, to weight 52 connections one after the other. We asked the stakeholders "How much does the value of concept A impact on the value of concept B (strong, medium or weak impact)?" (Wei et al. 2008, Carvalho 2013). The perceived amount of change a concept contributes to another is what is used and not the measure of certainty of the connection. The visual output of the previous step was provided in the online form to visualise the entire system's concepts and connections while stakeholders carried out pairwise associations weighting. A glossary of the original concepts in clusters and their generalised labels was also attached to the online form. The data were downloaded as spreadsheets and the qualitative weights were assigned the numerical values 0.9, 0.5, 0.1 for strong, medium and weak respectively.

3.3.6 STEP 6: Quantitative aggregation

The individual weightings per stakeholder are coded into separate spreadsheets to form adjacency matrices representing individual FCMs (Diniz et al. 2015). In the matrices, connections between concepts that are not part of the FCM are assigned zero and where connections exist, the weighted value is entered. With these data using a matrix-vector multiplication, the quasi-dynamic output of FCM was calculated for each stakeholder. In a real mathematical sense, the output is static rather than dynamic, so we adopt the term 'quasi-dynamic' to indicate the dynamic character of the interpretation of system changes (Jetter and Kok 2014). After multiple iterations, the values of concepts stabilise and the system attains a steady state. The number of iterations here is not related to time but to the relative influence concepts have on each other (Kok 2009, Diniz et al. 2015, Voinov et al. 2018).

To build an aggregate FCM the weighting outcomes for the participating stakeholders were quantitatively aggregated by using the mean value per connection. This combination of individual knowledge into one FCM is considered a representation of shared knowledge (Gray et al. 2015).

3.4 Results

3.4.1 Participating Stakeholders

By using the criteria and quota system, participating stakeholders included 6 from academia, 6 from research institutes, 6 farmers and 5 Government agency workers; from 11 states of Nigeria. 91% stakeholders (n=23) participated in the both episodes of stakeholder engagement (Supplementary material Table SM3.2) .

3.4.2 Concepts and Connections

The knowledge generation by stakeholders yielded concepts mentioned as phrases/ terms in many different forms. All original concepts mentioned (as variables, inputs, outputs, factors, values, states) by stakeholders and the generalised labels chosen for each group of concepts, with the scientific literature used to back these up are presented as Supplementary Material (Table SM3.3). There are a total of 28 concepts and 64 connections. The centrality describes a concept's total number of incoming and outgoing relationships in the FCM (Figure 3.5).

Not all concepts were mentioned by each stakeholder. The lowest mentioned concepts are 'GHG emissions', 'Deforestation and biodiversity-loss' and 'Soil degradation' which are all negative externalities of rice systems. All stakeholders mentioned the central concept 'Rice production' and 'Rice area'. The next highest mentions are 'Financing/subsidisation' and 'Government import restriction policies', followed 'Climate impacts'.

On the online form, a section was provided for comments to be added by stakeholders. Comments (Supplementary Material, SM 3.4) were received from 10 stakeholders. Stakeholders emphasised the importance of already mentioned concepts even using quantitative metrics such as percentages. Stakeholders also mentioned additional concepts such as farm size. Stakeholders made mention of the relevance of the study to the current situation reiterating that the results should be shared to decision makers.

3.4.1 FCM outputs

FCM graph

Each weight provided by each stakeholder represents the value of the influence of one concept on another (weights of connections) for their individual FCM. An average of all weights per connection provided a value for the aggregate FCM. The FCM consists of 28 concepts (C1 – C28) and 64 connections (Figure 3.6).

Some concepts have only outgoing arrows to other concepts and no incoming arrows. These concepts are termed driver concepts, they have a strong outgoing influence on the system. They also have a reinforcing effect on themselves effected in the dynamic FCM runs. Receiver concepts are influenced by other concepts but are themselves not influencing the system. These concepts – market price of local rice (C8) and GHG emissions (C28) are represented in the FCM with orange boxes (Figure 3.6). Feedback loops are another feature of FCMs and nine occur in this FCM. A feedback loop is a cycle of causal feedback in FCM. Feedback loops occur when a concept on activation serves as input to another concept but on causing the activation of other concepts becomes an output, causing a cyclic, non-linear behaviour in the system (Osoba and Kokso 2019).

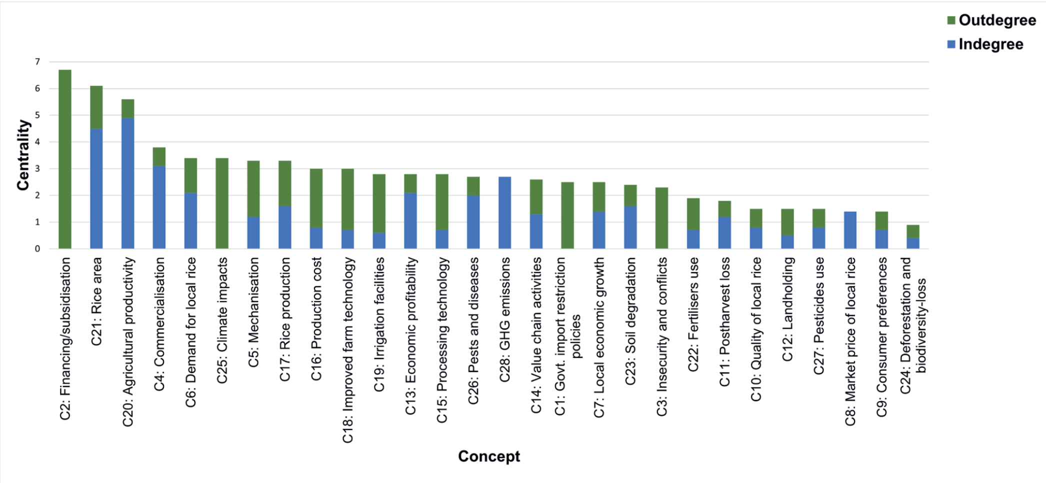


Figure 3.5 Concepts in the fuzzy cognitive map of Nigeria's rice agri-food system ordered by the centrality.

FCM dynamic output

The weights obtained from the second episode of stakeholder engagement yielded a simple matrix multiplication which produced a dynamic output indicating the state of the system. The model stabilised in the first attempt and so there was no need for further calibration.

3.5 Discussion

3.5.1 Benefits

Stakeholder engagement is enhanced: The challenges earlier mentioned that accompany group PM processes (Section 3.1.2) are eliminated or mitigated in the EAsy approach. The episodic nature of our approach can be implemented with the same stakeholders without extra challenges to their involvement after initial episodes. It is not often the case in PM settings that the same set of stakeholders can remain involved in all episodes of the PM process. In this study, 21 out of 23 stakeholders, 91% of initial participating stakeholders participated in the 2nd episode of the stakeholder engagement. Asynchronous participation of stakeholders addressed the challenge of retaining the presence of the same stakeholders between the PM stages while eliminating the logistic constraints of gathering people in one location at a suitable time.

Individual knowledge is elicited: Our approach also eliminates the power imbalances that often happen in group modelling settings. Possibly, a workshop setting might give rise to products reflecting the opinion of some and not all the stakeholders present. Not all stakeholders may be able to express the knowledge they carry where others are present due to power imbalances related to gender, cultural, socioeconomic status or the 'stronger' voices dominating the participatory process. Also, in seeking consensus among stakeholders, some opinions may be lost. FCMs built on individual participation allow stakeholders to express individual perception without being influenced or seeking to reach consensus with other stakeholders (Jetter and Kok 2014). It allows for a wider and deeper knowledge of the system with the diverse, rich understanding that each individual has about the system (Olazabal et al. 2018). Individual participation eliminates intersubjectivity that is a result of workshop settings(Penn et al. 2013, Knight et al. 2014). In any group of people, individual perspectives offer more insights than a group perspective shaped by consensus (Vervoort 2011). Thus the approach we employ is effective at individual knowledge elicitation from stakeholders.

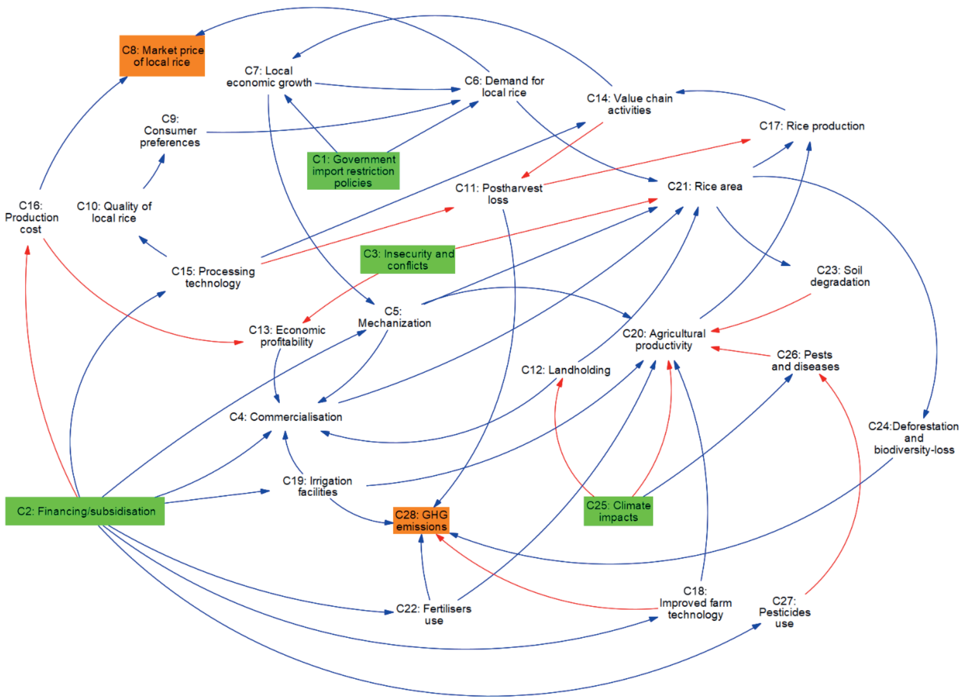


Figure 3.6 Fuzzy cognitive map of the Nigerian rice agri-food system showing concepts and connections. Red arrows represent inverse or negative connections, blue arrows represent direct or positive connections. The driver concepts are in green boxes and the receiver concepts are in orange boxes.

No prior technical skills or systems thinking needed: In many PM settings, where groups of stakeholders gather or where the researcher meets with an individual stakeholder for an interview, the FCM diagramming could be participatory. In one case, the stakeholder draws the diagram connecting concepts to concepts. In another case, the stakeholder supplies the knowledge while the researcher draws the diagram receiving feedback from the stakeholders. This structured mapping process is not always effective. Situations have been recorded where stakeholders may be uncomfortable with a structured mapping approach and so it may be better to capture their knowledge through interviews while the researcher does the diagramming (Fairweather 2010, van Vliet 2011, Vanwindekens et al. 2013). In this study, the individual stakeholders listed the concepts and the connections during the telephone interview while the researcher drew the diagram afterwards; therefore stakeholders did not participate in a structured FCM diagramming activity. The advantage is that no specific knowledge or familiarity with systems thinking is required. This allows for a broader engagement than a structured diagramming or group modelling activity. It also allows for a diversity of stakeholders to be involved since no prior technical knowledge nor systems thinking is required.

Choice of media promotes stakeholder inclusiveness: It is best to employ the media that is most comfortable to stakeholders, that allow them to provide knowledge and input and allow for the inclusion of diverse groups of stakeholders in the PM process (Butler and Adamowski 2015). We used individual telephone interviews and online form technology. The telephone has become the most important and common form of communication in the local context, Nigeria. Mobile phones, with easy-to-use touch screens, are easily accessible by stakeholders; providing a low barrier form of media for both episodes of stakeholder engagement. While using a video conferencing tool would have allowed for more interaction with stakeholders and possibly participatory diagramming of the FCM, in the local context (Nigeria) currently, the telephone is more stable than the internet. Therefore, using the most common media promoted the inclusiveness of all stakeholder groups in the PM.

Knowledge generation begins with stakeholder: Stakeholders were not offered a predefined list of concepts to choose from and so knowledge generation began with the stakeholders. Some studies offer stakeholders a predefined list with the reason that stakeholders can use identically worded concepts in drawing their individual FCM (Fairweather and Hunt 2011). Another reason given is that a predefined list saves time used by stakeholders in identifying concepts before drawing their FCM (Fairweather 2010, Fairweather and Hunt 2011). Providing a predefined list aims at drawing a map with concepts the researcher has pre-chosen and determined as what makes a 'proper' description of the system (Christen et al. 2015). This can be problematic because concepts selected and provided to stakeholders may not be the most relevant for people in the local context, or may use different wordings than what stakeholders are used to.

In this study, we aim to integrate several stakeholders' knowledge in understanding and mapping the system. Therefore, stakeholders generating their concepts allow the expression of their original knowledge and opinions on which concepts are of importance, without an influence from a list of concepts. When the differently worded concepts are qualitatively aggregated, we have an aggregate cognitive map that represents all stakeholder knowledge. We observed that different stakeholders mention same concepts using different terms (Supplementary Material, Table SM3.3). Allowing stakeholders this expression promotes inclusiveness of different stakeholder groups.

All Stakeholder knowledge is included: Each individual stakeholders emphasise the part of the system that they perceive as most relevant. If each stakeholder description is mapped into an individual FCM, their description will miss feedback loops (Gray et al. 2015). Including all stakeholder knowledge facilitated the piecing together of different parts of the system, which led to an understanding of the complexity of the system and showed the interplay between interdependent factors. We included all stakeholder knowledge to give equal credence to the knowledge of each stakeholder as their valid perception of the system. The inclusion of all stakeholder knowledge can be considered a strength, as the heterogeneity of stakeholder knowledge is reflected in the final FCM (Figure 3.6).

Use of scientific literature to support stakeholder knowledge: Concerns have been raised about the confusion that may arise on the use of generalised labels which were not agreed upon by stakeholders (Olazabal et al. 2018). Also, Fairweather and Hunt (2011) criticise the use of a qualitative aggregation which leads to generalised labels rather than providing a predefined list of concepts for stakeholders to choose from. They argue that this post-processing of stakeholder knowledge relies a lot on the researcher's subjective interpretation of stakeholder expressions. After knowledge elicitation from stakeholders, more decisions need to be made by the researcher as part of post-processing activities. This researcher subjectivity can tip the balance of co-production and researcher input may outweigh stakeholder input (Voinov et al. 2016). To mitigate these concerns, we use scientific literature to provide an objective way to aggregate stakeholder knowledge and allocate generalised labels to groups of concepts; thereby reducing subjective interpretation of stakeholder expressions. The most commonly used expressions in literature are used for concepts clustering, concepts generalised labels, in establishing sub-connections and filling in missing connections. To ensure stakeholder understands what the final terms used mean, in the 2nd episode of stakeholder engagement, on the online form for weighting connections, a glossary of the original concepts in clusters and their generalised labels is included for stakeholders (Supplementary materials Table SM3.3).

Aggregation method reduces loss of heterogeneity: PM processes often include qualitative and quantitative aggregation to put together individual cognitive maps or those of separate groups in one social/aggregate map (Diniz et al. 2015, Singh and Chudasama 2017, Singh et al. 2019). Aggregation can lead to the loss of heterogeneity in stakeholder perceptions (Mehryar et al. 2019). Some group modelling studies carry out quantitative aggregation before qualitative aggregation to arrive at a social aggregate cognitive map (Singh and Chudasama 2017, Singh et al. 2019). We moved from individual knowledge to aggregated knowledge in two steps. First, in Step 4, a qualitative aggregation is done on individual stakeholder knowledge through analysis, clustering into groups and allocating generalised labels to groups of concepts. In Step 5, stakeholders individually assigned weights to the same connections and these weights are qualitatively aggregated with the common mathematical average. By including all stakeholder knowledge and aggregating qualitatively before presenting for weighting, we retain the heterogeneity in stakeholder knowledge.

3.5.2 Drawbacks

Balance of co-production: Models are simplified representations of reality in which the process of simplification is guided by the knowledge and assumptions of those involved in the model development process ((Schlüter et al. 2019). When researchers and stakeholders are involved in the process, as is the case with PM, we want to ensure that the balance of co-production does not shift to the researchers. The main issue with the EAsy approach is that with asynchronous stakeholder participation, much of the PM post-processing activities rely on the researcher and these post-processing involves crucial decisions on the structure of the FCM. At the end of the process, the role of the researcher is relatively large as compared to the face-to-face PM settings such as group modelling. The researcher needs to have good interviewing and cognitive mapping skills and needs to be able to translate expert statements into an FCM (Jetter 2006). Like any interpretive approach, the knowledge elicitation and map diagramming are sensitive to the subjectivity of the researchers, their preferences, biases, as well as mapping skills (Elsawah et al. 2015).

Howbeit, we mitigate these risks and achieve a representation based on stakeholder knowledge by validating our decisions with previous scientific studies (Supplementary Material Table SM3.3). Jetter and Kok (2014) advise that a combination of map diagramming with face-to-face interviews will help stakeholders to carefully consider their mental models. This can still be achieved asynchronously by using online diagramming tools and other web services or video conferencing tools. The EAsy approach can be enhanced by use of technology to reduce the post-processing activities carried out by the researchers only.

Weighting Connections as pairwise associations and with linguistic values: We chose pairwise connection weighting as a participatory design to accommodate diverse stakeholders with their skills and knowledge. However, pairwise connection weighting has the drawback that the system may not be considered as a whole but as linear causalities only. We reduced the effect of this drawback by including in the online form a diagram of the mental model being weighted to provide a visualisation of the whole system to stakeholders. Also, instructions were included to consider the linear casualties being weighted as part of the system.

On the use of linguistic scales, the stakeholders must be weighting on purely linguistic scales so as not to confuse this with the weighting within the FCM where strengths are relative (Jetter and Kok 2014). From the additional comments provided by stakeholders, stakeholder A5 made a comment using numerical values to describe some connections; one of which is "*acceptability of local rice among consumers has improved significantly* *(about 70% by my perceived estimate)"* (see Supplementary Material List SM3.4). As is the case in this additional comment received, it is common for stakeholders to perceive the degree of change in the system in numerical values even though they are offered linguistic values for weighting connections. This raises concerns with the use of pairwise connection weighting whether stakeholders are weighting causalities in the system relative to each other in the FCM or with their numerical estimates of the system in reality.

Stakeholders use linguistic values of weak, medium and strong, which the researchers need to convert to numerical values. Realising the subjective character of the translation, we analysed the effect of various sets of numerical values (0.9/0.5/0.1; 0.9/ 0.6/0.3 and 0.8/0.5/0.3) on the dynamic output. We found that although absolute stabilising factors differ, in relative terms the outputs were very similar. In an aggregate map, the choice of weights has much less impact on the overall output as differences in assigned values average out.

Consideration of learning: Social learning and communication are an important part and aim of many PM processes and can be used for method appraisal in PM.

Although the goal of this study is to elicit and represent knowledge, an avenue to enhance social learning would have increased the benefits of the approach. In addition to the missing interactions between stakeholders, the approach would have benefitted from more interaction between the researchers and the stakeholders. A more detailed discourse and room for feedback during the map diagramming and other post-processing activities carried out by the researchers could enhance the final output. Stakeholder R7 as an additional comment in the 2nd episode mentioned an additional concept (family size) that was not mentioned earlier during the interviews. This indicates the need for other episodes of interaction between the PM steps to receive feedback from stakeholders on the intermediate and final products of the PM process. Also, an analysis may demonstrate changes in the ways individuals conceptualise the system as the result of interaction with the intermediate products and final model (Radinsky et al. 2017). Smetschka and Gaube (2020), in a workshop PM setting, presented the initial model design to stakeholders to fine tune to their perceptions via an interactive interface.

Further development of the EAsy method would benefit from the use of interactive interfaces to capture stakeholders concerns on the initial model design.

3.6 Conclusions

We finalise the paper by presenting the shortcomings of PM processes together with an assessment of the degree to which the EAsy method we applied in this paper can overcome them (Table 3.1). We finalise the paper showing how the EAsy method has the potential to decrease shortcomings in PM processes.

Table 3.1: Overview of how the methodology solves the challenges of PM processes

	Our approach		
	Eliminates the problem	Mitigates the problem	Still a problem
Logistic constraints with gathering people in one location at a suitable time for group modelling.	✓		
Inclusion of diverse groups of stakeholders even less organised groups and individuals		✓	
Ability to retain the interest and presence of the same stakeholders between the PM stages		✓	
Power imbalances where groups of stakeholders gather to share their perception of a system	✓		
Seeking consensus on contrasting viewpoints in group modelling sessions	✓		
Technical /structured modelling knowledge/systems thinking required of stakeholders	✓		
Parts of the system not included in the final model due to heterogeneity of stakeholder knowledge		✓	
Balance of co-production		✓	
Social learning			✓
Visual aids to enhance communication			✓
Room for feedback from stakeholders on intermediate products			✓

In this paper, we offered a structured method to elicit systems knowledge from stakeholders and represent this in an FCM. Our methodology was applied in a case study of the rice food system in Nigeria. This co-production method was characterised in time and space as episodic and asynchronous (EAsy). We also provided a detailed process with standardised reporting, ensuring transparency and reproducibility at every stage. Also, we offered a method that does not require special software or hardware, or specific qualities of stakeholders in systems thinking or FCM construction.

The emphasis of this paper is on the participatory process and methods. From this study we demonstrate that co-production can be achieved in PM settings without face-to-face interactions with stakeholders. The final output of this method is similar to that of other studies and can thus be considered equally valid to construct a representation of a complex social-ecological system. The output of this approach yielded a FCM of the current rice agri-food system of Nigeria. From the FCM, we developed a scenario framework, using the current situation as the baseline scenario, for which the current drivers apply. The dynamics of the FCM coupled with the scenario analysis contributed to the identification of system archetypes which are unsustainable patterns in the system. Embedded in the system archetypes are strategies to more desirable system outcomes. The three archetypes are 1) Limits to success (soil degradation reduces agricultural productivity necessitating rice area expansion) 2) Fixes that fail (expanding rice area fails to increase production because of low productivity) and 3) Drifting goals (government import restriction policies creates more food insecurity). In Chapter 4 of this thesis, the archetype analysis and strategies are discussed in detail.

From a methodological point of view, we can thus question the need for live, in-person participation as an indispensable component in the growing number of applications of participatory modelling. Especially in the light of health pandemics and the urgent need to reduce our carbon footprint, an approach like we apply offers an alternative to live, in-person participation. Research engaged in participatory processes with local stakeholders should decide for which issues and in which phases certain participatory elements could be implemented with asynchronous stakeholder participation. Further research should explore how asynchronous participation of stakeholders in participatory processes can benefit from technological advancement, especially with incorporating the use of visuals. It is important to emphasise that specific cases should use the media outlets that present low entry and usability barriers to the stakeholders involved while achieving the purpose of the PM.

Chapter 4

Identifying system archetypes in Nigeria’s rice agri-food system using fuzzy cognitive mapping

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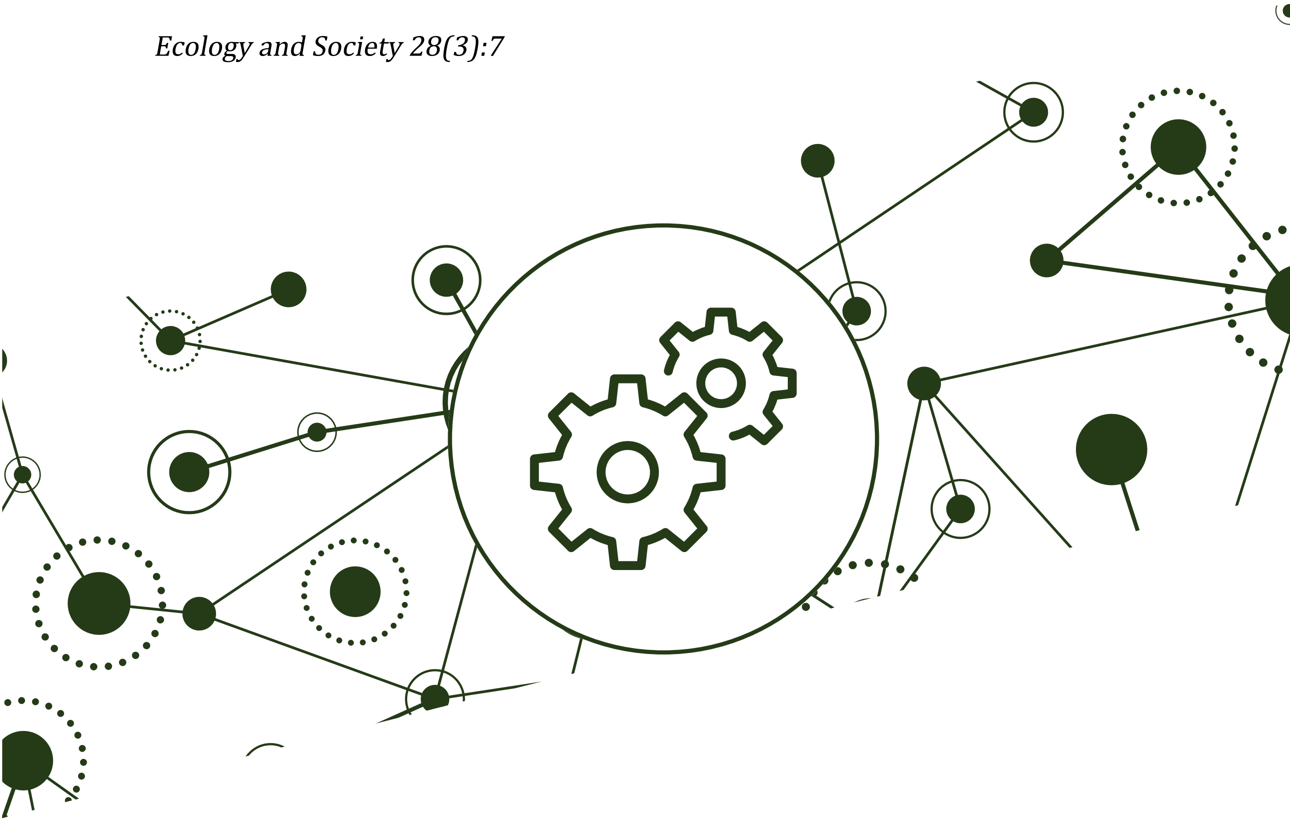

Abstract

Nigeria is a major rice-producing and rice-importing country in Africa, challenged with ensuring rice-food security for its growing population. Successive governments have implemented several strategies to increase local rice production such as rice import restriction policies and agricultural investments. These strategies have yielded results but achieving long-term sustainable growth in Nigeria's rice agri-food system has remained elusive. Addressing food security and sustainability in agri-food systems requires a systems-thinking approach. In this study, we applied two systems thinking techniques, fuzzy cognitive mapping (for describing the system structure and behaviour) and archetype analysis (to reveal generic system archetypes and effective strategies to improve the system). Our analysis revealed three system archetypes: limits to success, fixes that fail and drifting goals. Rice production is limited by low agricultural productivity indicating the 'limits to success' archetype. Farmers tend to increase rice area as a 'quick fix' to productivity issues but this quick fix leads to unintended consequences such as soil degradation (fixes that fail archetype). Additionally, because of the import-restriction policies generating an unmet demand for rice, the government may face pressure to lower the goal of self-sufficiency falling into the 'drifting goals' archetype. However, our analysis shows that suspending import-restriction policies would result in undesirable system states, with reduced demand for local rice and lower rice production. Our results underscore the importance of government policies in increasing rice production sustainably and ensuring food security.

4.1 Introduction

4.1.1 Background of study

Rice has become a staple food in Africa (Seck et al. 2013, van Oort et al. 2015). Although Africa has recorded a six percent annual growth in rice production over the last decade (OECD/FAO 2016), rice production in Africa still struggles to meet rising rice demand (van Oort et al. 2015, Van Ittersum et al. 2016). As a result, Africa's rice imports have increased, causing a dependence on the international markets, with risks of economic strains, food insecurity and conflicts due to the volatility of rice prices (Seck et al. 2013, Mendez-del-Villar and Lançon 2015). For example, the 2008 global price hike resulted in food riots in several African cities in response to the soaring rice prices (Seck et al. 2013).

On the other hand, rice consumption will keep increasing because of urbanisation, rising household incomes and population growth in Africa. However, climate change and variability threaten rice production (Roudier et al. 2011, Terdoo and Feola 2016). Given these issues, many African governments aim to address rice production deficits to increase rice supply at a growth rate greater than rice consumption (Arouna et al. 2021).

In addition to government efforts, there has been a long focus of research on the development of Africa's rice agri-food system, examining the national, sub-regional and regional potential for growth (Andriesse and Fresco 1991, Balasubramanian et al. 2007, Otsuka and Larson 2013, Saito et al. 2013, Rodenburg et al. 2014, Nasrin et al. 2015, van Oort et al. 2015, Van Ittersum et al. 2016, Niang et al. 2017). These strands of literature have highlighted various factors affecting rice agri-food system development, such as macro-economic factors (trade relations, import laws, government expenditure on agriculture), productivity issues emanating from farm technology, soil fertility, rice growing environments and commercial factors such as prices. These factors represent multiple ways to intervene in a given agri-food system (Foran et al. 2014).

The untapped potential for increasing rice production in Africa is widely agreed upon, yet rice production still lags behind rice demand. Addressing this gap requires systems thinking rather than linear approaches (Liu et al. 2015, Allen and Prosperi 2016, Zhang et al. 2018, Ruben et al. 2019, Borman et al. 2022). Systems thinking manages the complexity of agri-food systems to ensure desirable outcomes (Foran et al. 2014, Zhang et al. 2018, Bustamante et al. 2021). System thinking is operationalized through various tools and techniques, such as causal loop diagrams, stock and flow models, fuzzy cognitive maps and archetypes (Senge 1990, Forrester 1994, Coyle and Alexander 1997, Homer and Oliva 2001). These tools and techniques account for the various components of the system that constitute its structure, causal connections and feedback loops, which result in the system's behaviour.

Our study uses archetypes as building blocks to analyse a system as a whole of causal mechanisms (Oberlack et al. 2019). We derive feedback loops, also called causal loops, from fuzzy cognitive mapping and match these system structure components with generic structural patterns, which are the system archetypes. System archetypes are often based on causal loop diagrams (Senge 1990, Kim and Lannon 1997, Wolstenholme 2003), but we innovatively base our system archetypes on fuzzy cognitive maps in this study. Fuzzy cognitive maps are similar to causal loop diagrams in applying graph theory for qualitative system modelling (Voinov et al. 2018). However, fuzzy cognitive mapping incorporates quantitative simulation to analyse the system's behaviour, providing information based on its structure and behaviour, which can be adjusted toward desirable behaviours. Our study applies these methods to understand and analyse the structure and behaviour of the Nigerian rice agri-food system and to propose effective solutions to address the problems embedded in the system.

4.1.2 Study area

We identified Nigeria as a suitable study area. Nigeria is Africa's highest rice producer and consumer (FAOSTAT 2022). Nigeria is in West Africa, bounded to the north by the Republics of Niger and Chad; to the South by the Atlantic Ocean; to the east by the Republic of Cameroun; to the West by the Republic of Benin. Nigeria is part of the West African rice belt, Africa's dominant rice-producing and consuming region, which has experienced the highest rice demand growth rate globally (Rutsaert et al. 2013, Mendez-del-Villar and Lançon 2015).

Nigeria has a land area of 92.38 million hectares, with less than 1% equipped for irrigation (FAOSTAT 2022). In Nigeria, rice is mainly produced in four of the six sub-regions of Nigeria: the North central region (31% of national production), the North West region (30%), the North-East region (24%) and the South-East region (8%; USDA 2022). In 2019, Nigeria was the 14th top producer of rice in the world at a volume of 8 million tonnes (USDA 2022). An increase in rice area rather than improved yield accounts for most of Nigeria's rice production increase (Figure 4.1). The rice area has increased substantially between 1961 and 2019, whereas the national yield has remained almost unchanged, below 2.5 tonnes per hectare, rising by only 78% between 1961 and 2019 (Figure 4.1).

Nigeria is challenged with ensuring rice-food security for its growing population of 200 million people. Nigeria is ranked seventh by population in the world and could rise to third by 2050 (United Nations 2022). Rice production has increased, but so has rice consumption, necessitating rice imports to meet rice demand. By 2035, it is estimated that Nigerians will more than double their rice consumption compared to 2010 (Seck et al. 2013).

The Nigerian government has attempted to achieve rice self-sufficiency through various strategies, including agricultural investments and market protectionist measures such as import-restriction policies. Import bans have been implemented in the past such as those between 1986 and 1995 (Oyejide et al. 2013, Mendez-del-Villar and Lançon 2015). More recently, in 2015 and 2017, restrictions on foreign exchange for rice trade and a ban on imports through seaports and land borders were implemented, respectively (Ugwuja and Chukwukere 2021). These policies aim to boost demand for local rice while creating more support for farming through mechanisation, importing high-yielding seeds and providing subsidies and loans to farmers (Onyiriuba et al. 2020).

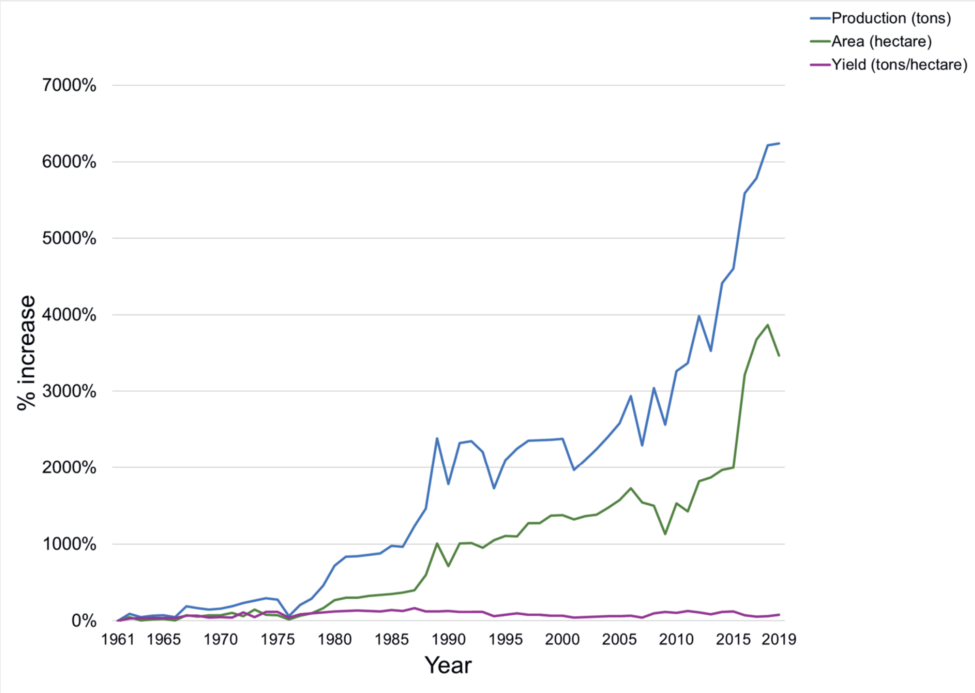

Figure 4.1: Changes in rice production (tons), harvested area (hectares) and yield (tons/hectare) in Nigeria from 1961 to 2019. The percentage increases are indexed relative to their values in 1961 (equivalent to 0). Data sources: FAOSTAT; Image: Authors compilation.

4.2 Methodology

The first step in our study was identifying the factors, also called concepts, that make up the system structure. We did so with fuzzy cognitive mapping using stakeholder knowledge gathered through interviews. The system structure was then analysed to derive dynamics representative of the system behaviour. Furthermore, we matched our system structure and behaviour to system archetypes and proposed strategies to improve the system. Figure 4.2 shows how we combined fuzzy cognitive mapping and system archetypes in an analytical framework.

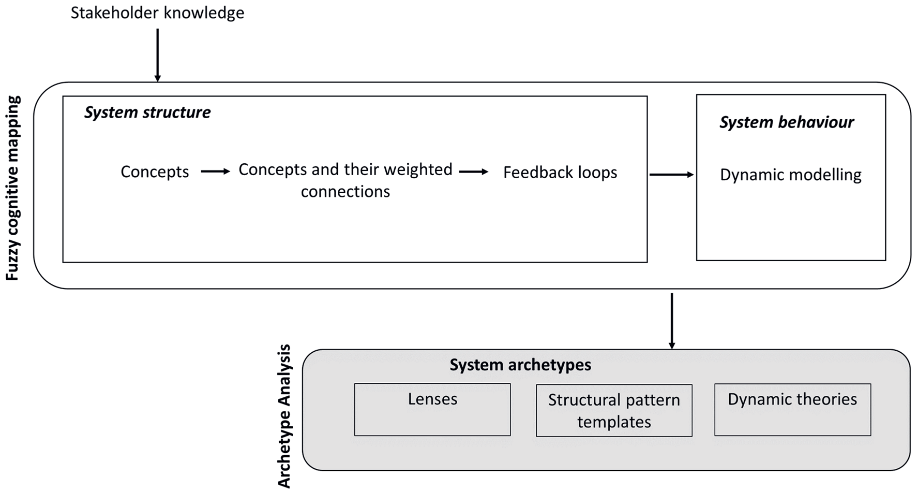

Figure 4.2: Analytical framework showing the combination of fuzzy cognitive mapping and archetype analysis

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4.2.1 Fuzzy Cognitive Mapping

Fuzzy cognitive mapping relies on graph theory to visually represent the system structure as an output of cause-and-effect connections between the system concepts (Yoon and Jetter 2016). The main elements of a fuzzy cognitive map (FCM) are nodes or concepts (C1, C2, C3..., Cn), directed edges (C1 → C2, etc.) as a set of arrows or arcs that represent the connection between concepts. However, a fuzzy cognitive map (FCM) is not just a system visualisation or diagramming tool for showing causation. The FCM also operates as a mathematical model, thus providing a dynamic hypothesis and not only an explanatory map (Homer and Oliva 2001). This attribute enables a broader application of fuzzy cognitive mapping in modelling, simulation, what-if analyses and integrated assessments (Rezaee et al. 2017, Voinov et al. 2018, Bakhtavar et al. 2021).

The FCM is a mathematical model using an adjacency matrix containing all connections' weights (Kok 2009). When a concept changes its state, it affects all other concepts causally linked to it and the affected concepts subsequently change their state (Jetter and Kok

2014). In other words, concepts evolve dynamically depending on their nodes and spread through the graph until the dynamic output is stabilised (Helfgott et al. 2015). Fuzzy cognitive mapping investigates feedback loops that cause iterating activation and change of concepts through the model until the system reaches a stable state (Nápoles et al. 2016). These dynamics from the initial state towards a stable state provide the principal insights of fuzzy cognitive mapping applications, which can be further applied to understand the behaviour of complex systems (Kok 2009, Rezaee et al. 2017). Fuzzy cognitive mapping can handle this dynamic complexity of the system because the system behaviour emerges from the change from concepts spreading through other concepts until the system reaches a stable state. FCMs also allow analysis through hypothetical scenarios to investigate how the system reacts to varying conditions. Such scenario analysis is carried out by using different input vectors, which contain activation levels ranging from 0 to 1, resulting in different scenarios of the system (Papageorgiou and Kontogianni 2012).

FCM can be developed through a participatory process as a group modelling exercise (van der Sluis et al. 2019) by eliciting knowledge from stakeholders through interviews (Edwards and Kok 2021) or through a literature review (Jetter and Kok 2014, Olazabal et al. 2018). When using a participatory process or stakeholder knowledge, an FCM typically combines individual cognitive maps into a collective mental model of the system, considered as shared knowledge (Gray et al. 2015, Olazabal et al. 2018). However, it is important to note that an individual's map may be subjective and not thoroughly describe the system. To mitigate this, involving multiple participants and aggregating their knowledge into one map is necessary. This participatory approach captures system complexity and enables stakeholder knowledge to be used for model simulation of system behaviour (Kok 2009).

Fuzzy Cognitive Mapping of Nigeria's rice agri-food system

We interviewed stakeholders to capture their perceptions into an aggregate FCM. We identified stakeholders from key institutions working in rice-related activities and using snowballing. The participating stakeholders were engaged in rice-related activities, 23 in total, with six from research institutes that not only conduct research but also carry out extension services, six from academic universities, six farmers and five government officials.

Stakeholder engagement occurred in two rounds. In Round 1, semi-structured interviews were conducted independently with each stakeholder. Knowledge was elicited from stakeholders on the current trends of Nigeria's rice agri-food system, with rice production as the central concept. Stakeholders were asked about the uncertainty and impact of key factors on the system enabling or constraining rice production (Interview questions are given in Supplementary material Table SM3.1). Next, we qualitatively aggregated stakeholders' knowledge (following Olazabal et al. 2018).

In Round 2, we presented the aggregated results from Round 1 in an online questionnaire. Stakeholders provided weights for each connection presented as pairwise connections (following Roberts 1976). We included a preliminary FCM linking all the connections to visualise the system structure easily. Stakeholders commented on the preliminary FCM and provided weights to pairwise connections. A detailed description of the process of FCM development using stakeholder knowledge is described fully in Chapter 3 of this thesis. The comments and weights provided by stakeholders were aggregated and used to build the FCM, which represents the current system description of the system. The aggregation process was supported with scientific literature and following established protocol to preserve stakeholders knowledge while keeping the authors' contribution minimal in the co-production process (Alizadeh and Jetter 2017, Olazabal et al. 2018, Edwards and Kok 2021). The properties of the FCM such as the indegree, outdegree and centrality were determined. The sum of the weights of the incoming connections is the indegree and the sum of the weights of the outgoing connections is the outdegree, whereas the centrality is the sum of the indegree and outdegree of each concept. The centrality of a concept reflects how related the concept is to other concepts and thus, its relative importance in the system (Gray et al. 2014). We also identified different kinds of concepts. The driver concepts have zero in-degree (i.e. only outgoing connections but no incoming connections from the system) while receiver concepts have zero outdegrees. Other concepts affect receiver concepts, but receivers do not affect the rest of the system.

We thereafter conducted dynamic modelling of the FCM using the Dynamic Analysis of Fuzzy Concepts in Evolving Systems (FuzzyDANCES) software version 2.0.1.0, which is part of the COMPASS multi-scale agricultural modelling framework (Groot et al. 2012, as cited in Aravindakshan et al. 2021). For the inference rules in the model, four concepts considered drivers in the system were clamped with a static activation value of +1, whereas the other concepts were set with an initial activation value of 0. This allows us to produce scenarios of plausible states of the system, by changing the static activation value of the driver concepts from a maximum of +1 to a minimum of +0.1. In all scenarios, we applied an objective function optimised to target value and not within a specified range and a multiplication function in which the new state of a concept is independent of the current state of the concept following the equation:

$$A_i(k+1) = f\left\{\sum_{j=1}^{N}(A_j\,(k).\;W_{ji}\,)\right\}$$

(Eq. 1)

where k is the iteration number, $A_i(k)$ and $A_i(k+1)$ are the state values of concept i at iterations k and $k+1$, $A_j\,(k)$ is the value of concept j at iteration step k and W_{ji} is the weight of the connection between concepts j and i. No transformation function was applied, so the concepts were not constrained to a certain range, allowing for quantitative simulation (Stach et al. 2005, Gray et al. 2015).

Sensitivity analyses of the model assess the relative importance of independent variables to the dependent variables (Chan et al. 2000, Lavin and Giabbanelli 2017). We analysed the model's variance with FuzzyDANCES using the winding stairs sensitivity algorithm (Chan et al. 2000) through 1000 windings per driver. The drivers were varied with a multiplication factor set to a maximum of 1, whereas the other concepts varied according to the matrix multiplication of the model. Using regression analysis, we tested the sensitivity of each driver concepts to the other concepts. In the FuzzyDANCES software, we also identified the feedback loops in the system. A balancing feedback loop contains negative feedback and stabilises dynamics, whereas a reinforcing loop gives positive feedback and accelerates dynamics in the system (Lannon 2012).

4.2.2 Archetype analysis

In applying systems thinking, researchers and practitioners must understand the underlying system structure and the resulting system behaviour and determine how to improve that structure to generate desirable behaviour (Schoenberg et al. 2020). The system structure is first described and often visualised. In our study, we describe and visualise the system structure using Fuzzy Cognitive Mapping and then further analyse the system structure using Archetype analysis.

Archetype analysis takes the building blocks of the system (the system structure) and matches them to generic system structures and behaviour patterns representing various phenomena in the complex systems (e.g. Banson et al. 2016). Archetype analysis can also identify patterns across many cases which are then classified into groups (Oberlack et al. 2019, Sietz et al. 2019). Then, each group is defined by a separate archetype (e.g. Vaclavik et al. 2013).

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Our study focuses on the former, taking the building blocks (the system structure) and matching them to system archetypes. These system archetypes are generic, described in the literature and used to explain complex system structure and behaviour. These include drifting goals, escalation, fixes that fail, growth and underinvestment, limits to success, shifting the burden, success to the successful and tragedy of the commons (Senge 1990, Kim and Anderson 1998, Kim 2000) . Furthermore, each system archetype has prescriptions for designing systemic interventions (Kim 1995; Table 4.1).

Archetype analysis can be used as a diagnostic tool; as a lens for deepening inquiry (Box 4.1), as structural pattern templates for identifying problems, as dynamic system theories, for predicting behaviour and to reveal embedded strategies to improve a system (Senge 1990, Kim 1995, Wolstenholme 2003).

Table 4.1. *Archetypes, dynamic theories and prescriptive actions (Source: Kim 1995)*

Archetype	Dynamic Theory	Prescriptive Actions
Drifting Goals	The 'Drifting Goals' archetype states that a gap between a goal and an actual condition can be resolved in two ways: by taking corrective action to achieve the goal, or by lowering the goal. It hypothesizes that when there is a gap between the goal and the actual condition, the goal is lowered to close the gap. Over time, the continual lowering of the goal will lead to gradually deteriorating performance.	Anchor the goal to an external frame of reference to keep it from sliding (e.g. benchmarking, voice of the customer). Determine whether the drift in performance is the result of conflicts between the stated goal and implicit goals in the system (such as current performance measures). Establish a clear transition plan from current reality to the goal, including a realistic time frame for achieving the goal.
Escalation	The 'Escalation' archetype occurs when one party's actions are perceived by another party to be a threat and the second party responds in a similar manner, further increasing the threat. It hypothesizes that the two balancing loops will create a reinforcing figure-8 effect, resulting in threatening actions by both parties that grow exponentially over time.	Identify the relative measure that is pitting one party against another and explore ways it can be changed or other ways the two parties can differentiate themselves in the marketplace. Quantify significant delays in the system that may be distorting the nature of the threat. Identify a larger goal that encompasses the individual goals of both parties.
Fixes That Fail	The 'Fixes That Fail' archetype states that a 'quick-fix' solution can have unintended consequences that exacerbate the problem. It hypothesizes that the problem symptom will diminish for a short while and then return to its previous level, or become even worse over time.	Focus on identifying and removing the fundamental cause of the problem symptom. If a temporary, short-term solution is needed, develop a two-tier approach of simultaneously applying the fix and planning out the fundamental solution. Use the archetype to map out potential side effects of any proposed interventions.
Growth and Underinvestment	The 'Growth and Underinvestment' archetype applies when growth approaches a limit that can be overcome if capacity investments are made. If a system becomes stretched beyond its limit, however, it will compensate by lowering performance standards, which reduces the perceived need for capacity investments. It also leads to lower performance, which further justifies underinvestment over time.	Identify interlocked patterns of behaviour between capacity investments and performance measures. Shorten the delays between when performance declines and when additional capacity comes on line (particularly perceptual delays about the need to invest). Anchor investment decisions on external signals, not on standards derived from past performance.
Limits to Success	The 'Limits to Success' archetype states that a reinforcing process of accelerating growth (or expansion) will encounter a balancing process as the limit of that system is approached. It hypothesizes that continuing efforts will produce diminishing returns as one approaches the limit.	Focus on removing the limit (or weakening its effects) rather than continuing to drive the reinforcing processes of growth. Use the archetype to identify potential balancing processes before they begin to affect growth. Identify links between the growth processes and limiting factors to determine ways to manage the balance between the two.

Shifting the Burden/Addiction	The 'Shifting the Burden' archetype states that a problem symptom can be resolved either by using a symptomatic solution or applying a fundamental solution. It hypothesizes that once a symptomatic solution is used, it alleviates the problem symptom and reduces pressure to implement a more fundamental solution. The symptomatic solution also produces a side effect that systematically undermines the ability to develop a fundamental solution or capability.	Focus on the fundamental solution. If necessary, use the symptomatic solution only to gain time while working on the fundamental solution. Elicit multiple viewpoints to differentiate between fundamental/symptomatic solutions and to gain consensus around an action plan. Use the archetype to explore potential side effects of any proposed solution.
Success to the Successful	The 'Success to the Successful' archetype states that if one person or group (A) is given more resources than another equally capable group (B), A has a higher likelihood of succeeding. It hypothesizes that A's initial success justifies devoting more resources to A, further widening the performance gap between the two groups over time.	Evaluate the current measurement systems to determine if they are set up to favour established practices over other alternatives. Identify goals or objectives that will define success at a higher level than individual players 'A' and 'B.' Calibrate internal views of market success against external indicators to identify potential competency traps.
Tragedy of the Commons	The 'Tragedy of the Commons' archetype identifies the causal connections between individual actions and the collective results (in a closed system). It hypothesizes that if the total usage of a common resource becomes too great for the system to support, the commons will become overloaded or depleted and everyone will experience diminishing benefits.	Establish methods for making the cumulative effects of using the common resource more real and immediate to the individual users. Re-evaluate the nature of the commons to determine if there are ways to replace or renew (or substitute for) the resource before it becomes depleted. Create a final arbiter who manages the use of the common resource from a whole-system level.

When archetype analysis incorporates stakeholder perspectives in a bottom-up fashion, insights into potential management solutions in the local context can be derived (e.g. Banson et al. 2016) and local findings linked with global findings (e.g. Moallemi et al. 2022).

Studies on agriculture and farming systems (Banson et al. 2016, Sharif and Irani 2016, Brzezina et al. 2017, Neudert et al. 2019, Nyam et al. 2022) have applied system archetypes to identify systemic problems and to propose solutions to achieve desired outcomes. System archetypes applied to agriculture and farming systems draw insights into root causes and underlying interacting mechanisms driving unsustainability outcomes (Neudert et al. 2019, Nyam et al. 2022).

Archetype analysis of Nigeria's agri-food system

After collecting stakeholder knowledge on the system and mapping the FCM, we implemented a step-by-step approach to identify system archetypes in Nigeria's rice agri-food system. First, we applied the 'lenses' (Box 4.1) to analyse the stakeholder knowledge. We deepened our inquiry into the system by asking the specific questions provided (Box 4.1). Next, we compared and matched the system structure (the FCM) with the structural pattern and dynamic theory of the generic system archetypes (Kim 1995; Table 4.1). Furthermore, we examined the FCM's dynamics, with the scenarios analysis and sensitivity analysis results to further understand how the system responds to change.

4.3 Results and Discussion

4.3.1 FCM properties

The aggregated FCM has a total number of 28 concepts and 64 connections (Figure 4.3) with more properties of the FCM such as weights in a connection matrix (Supplementary Material Table SM4.1) and a description of concepts is provided in Supplementary Material (Table SM4.3). An example of the FCM drawn in FuzzyDances software is presented in Figure SM4.3 (Supplementary material). The indegree, outdegree and centrality of the concepts are given in Figure 3.5 (Chapter 3 of this thesis). According to our results, the system is influenced mainly by Financing and subsidisation (C2) and rice area (C21) which have the highest centrality, whereas deforestation and biodiversity-loss (C24) and consumer preferences (C9) have the lowest centrality.

Four of the concepts are driver concepts because of their characteristics of high uncertainty and high impact on the system: government import restriction policies (C1), financing and subsidisation (C2), insecurity and conflicts (C3) and climate impacts (C25). Two concepts are receiver concepts: the market price of local rice (C8) and greenhouse gas (GHG) emissions (C28).

We identified nine feedback loops: six reinforcing feedback loops and three balancing feedback loops (Figure 4.4). For example, loop R1 is a reinforcing feedback loop showing how commercialisation increases rice area. Rice area expansion increases rice production, which leads to more economic benefits from rice production and further increases interest in the commercial farming of rice.

Box 4.1

Lenses to deepen inquiry and identify system archetypes in a system (Kim and Lannon 1997)

Questions to ask when putting on each of the archetype lenses

Drifting Goals

- Are there goals or standards that are eroding over time?
- Are people focused on achieving the goal or on reducing the discomfort of not achieving the goal?

Escalation

- Are there two or more players of equal power whose individual actions can be perceived as a threat by the others?
- Does each player have the capacity to retaliate with similar actions?

Fixes That Fail

- Have actions been taken to respond quickly to a crisis without much consideration of long-term consequences?
- Have similar actions been taken in the past in response to similar crises?

Growth and Underinvestment

- Do investments tend to be made as a reaction to growth rather than in anticipation of growth?
- Do problems created by growth, rather than long-range planning, act as the organizational signal to invest?

Limits to Success

- Are once-successful programs experiencing diminishing returns?
- Are there limits in the system that are constraining the growth?

Shifting the Burden

- Are actions that were taken to alleviate problem symptoms shifting attention away from more fundamental solutions?
- Are there additional consequences that systematically erode the underlying capability of the organization?

Success to the Successful

- Are there two or more equal options whose investment decisions are linked in a zero- sum game?
- Does the success of either option depend on initial conditions?

Tragedy of the Commons

- Is there a large number of equal players who have free or equal access to a common and limited resource?
- Is the system set up to be self-regulated, with no overarching governing body?

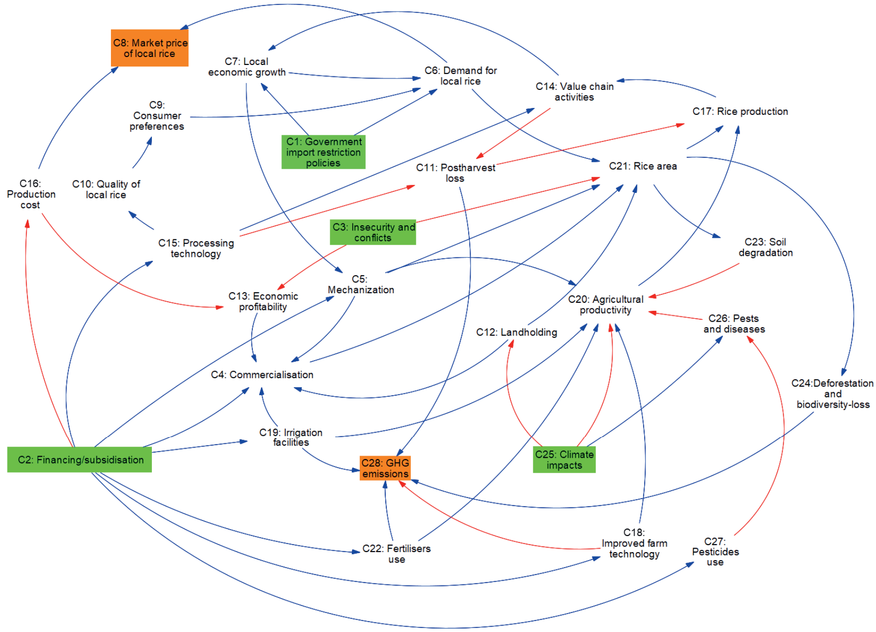


Figure 4.3: Fuzzy Cognitive Map of Nigeria's rice-agri-food system showing concepts and connections. Red arrows represent inverse or negative connections, blue arrows represent direct or positive connections. The driver concepts are in green boxes while the receiver concepts in orange boxes.

For the FCM dynamic modelling, the model stabilized without further calibration between 30 and 50 iterations. The sensitivity analysis demonstrated that the system is more sensitive to shifts in financing and subsidisation, as seen by the high correlation values, which account for most of the variance in the system (Table 4.2). Furthermore, the scenarios indicate the direction in which the system will likely move with or without policy interventions (C1, C2), climate change and insecurity challenges (C3, C25; Figure 4.5).

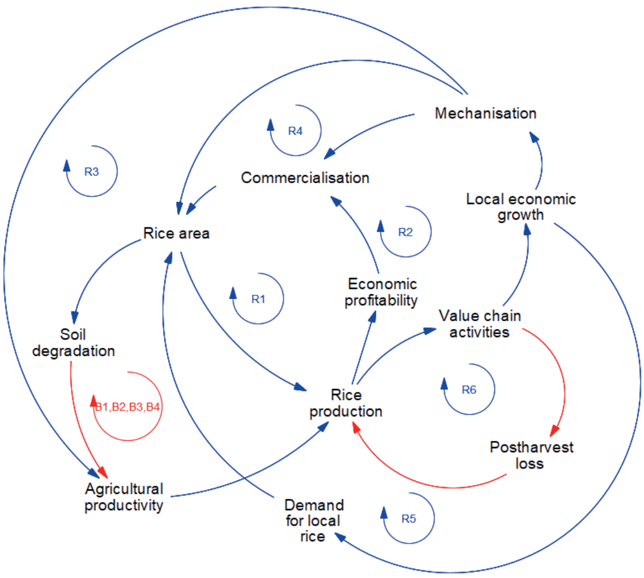


Figure 4.4 Reinforcing (R) and balancing (B) feedback loops in the fuzzy cognitive map of Nigeria's rice agri-food system. Red arrows represent inverse or negative connections, blue arrows indicate direct or positive connections. The loops are,

R1: Commercialisation - Rice area - Rice production - Economic profitability - Commercialisation
R2: Mechanisation - Commercialisation - Rice Area - Rice production - Value chain activities - Local economic growth - Mechanisation
R3: Mechanisation - Agricultural productivity - Rice production - Value chain activities - Local economic growth - Mechanisation
R4: Mechanisation - Rice area - Rice production - Value chain activities - Local economic growth - Mechanisation
R5: Demand for local rice - Rice area - Rice production - Value chain activities - Local economic growth - Demand for local rice
R6: Value chain activities - Postharvest loss - Rice production - Value chain activities
B1: Commercialisation - Rice area - Soil degradation - Agricultural productivity - Rice production - Economic profitability – Commercialisation
B2: Mechanisation - Commercialisation - Rice area - Soil degradation - Agricultural productivity - Rice production - Value chain activities - Local economic growth - Mechanisation
B3: Mechanisation - Rice area - Soil degradation - Agricultural productivity - Rice production - Value chain activities - Local economic growth - Mechanisation
B4: Demand for local rice - Rice area - Soil degradation - Agricultural productivity - Rice production - Value chain activities - Local economic growth - Demand for local rice.

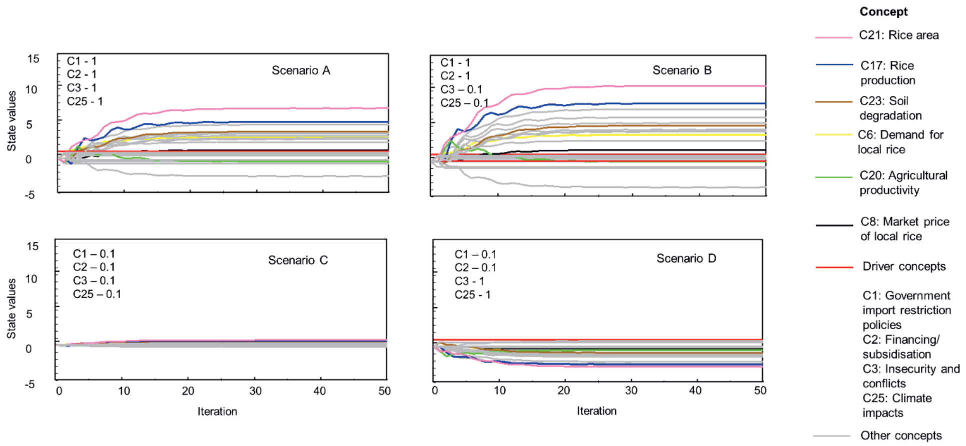


Figure 4.5: Four scenarios showing the outcome of the change in the influence of the drivers on Nigeria's rice agri-food system. C1: Government import restriction policies, C2: Financing/subsidisation, C3: Insecurity and conflicts, C25: Climate impacts

4.3.1 System Archetypes in Nigeria's rice agri-food system

We identified three system archetypes – limits to success, fixes that fail and drifting goals described below with the potential strategies for Nigeria's rice agri-food system context.

Limits to success (soil degradation reduces agricultural productivity, necessitating rice area expansion)

In the limits to success archetype, a reinforcing feedback loop (R) is constrained from accelerated growth by a balancing (B) loop (Figure 4.6) (Kim and Lannon 1997, Kim and Anderson 1998). We identified the limits to success archetype in Nigeria's rice agri-food system. Rice area expansion leads to environmental consequences, such as soil degradation, declining agricultural productivity and constraints on rice production (Figure 4.6).

Table 4.2: Overview of R2 values and regression coefficients (Coeff) of linear correlations between drivers and concepts. C1: Government import restriction policies, C2: Financing/subsidisation, C3: Insecurity and conflicts, C25: Climate impacts

	C1		C2		C3		C25	
	R^2	Coeff	R^2	Coeff	R^2	Coeff	R^2	Coeff
C4: Commercialisation	0.0319	1.2339	0.8779	6.5501	0.0207	-0.9963	0.067	-1.8019
C5: Mechanisation	0.0730	0.6756	0.8838	2.3775	0.0046	-0.1697	0.0397	-0.5015
C6: Demand for local rice	0.3179	1.6029	0.6388	2.2988	0.0066	-0.2315	0.0437	-0.5986
C7: Local economic growth	0.1276	1.3319	0.7910	3.3551	0.009	-0.3552	0.0738	-1.0201
C8: Market price of local rice	0.5728	0.9529	0.3369	0.7393	0.0134	-0.1461	0.0837	-0.3669
C9: Consumer preferences	0.0002	0.0054	1.0000	0.3920	0.0001	0.0044	0.0001	0.0048
C10: Quality of local rice	0.0002	0.0077	1.0000	0.5600	0.0001	0.0063	0.0001	0.0068
C11: Postharvest loss	0.0255	-0.5474	0.9001	-3.2873	0.0068	0.2836	0.0646	0.8769
C12: Landholding	0.0002	-0.0063	0.0001	-0.0061	0.0006	-0.0125	1.0000	-0.5
C13: Economic profitability	0.0320	1.0717	0.8389	5.5556	0.0441	-1.2607	0.0823	-1.7328
C14: Value chain activities	0.0319	0.9027	0.8726	4.7788	0.009	-0.4805	0.0833	-1.47
C15: Processing technology	0.0002	0.0097	1.0000	0.7000	0.0001	0.0079	0.0001	0.0085
C16: Production cost	0.0002	-0.0111	1.0000	-0.8000	0.0001	-0.009	0.0001	-0.0097
C17: Rice production	0.0378	1.4932	0.8466	7.1480	0.0111	-0.81	0.1011	-2.4599
C18: Improved farm technology	0.0002	0.0097	1.0000	0.7000	0.0001	0.0079	0.0001	0.0085
C19: Irrigation facilities	0.0002	0.0083	1.0000	0.6000	0.0001	0.0067	0.0001	0.0073
C20: Agricultural productivity	0.1509	-0.5077	0.1451	0.5036	0.1448	0.4982	0.552	-0.9782
C21: Rice area	0.0694	2.4844	0.8452	8.7685	0.0278	-1.5743	0.0579	-2.2854
C22: Fertilisers use	0.0002	0.0097	1.0000	0.7000	0.0001	0.0079	0.0001	0.0085
C23: Soil degradation	0.0845	1.2448	0.8703	4.0416	0.0327	-0.776	0.0161	-0.547
C24: Deforestation and biodiversity- loss	0.0694	0.9938	0.8452	3.5074	0.0278	-0.6297	0.0579	-0.9142
C26: Pests and diseases	0.00	-0.0048	0.6563	-0.9714	0.00	0.0065	0.3321	0.6881
C27: Pesticides use	0.0002	0.0111	1.0000	0.8000	0.0001	0.009	0.0001	0.0097
C28: GHG emissions	0.0534	0.8785	0.8457	3.5380	0.0188	-0.5227	0.0806	-1.0874

In the current system, the balancing feedback loops (B1, B2, B3) dampen rice production (R1, R2, R4, R5) through soil degradation-related losses in agricultural productivity, hence serving as a 'limit to success' of rice production. The archetype replicates the depletion of natural resources through anthropogenic exploitation (Meadows et al. 1972). By eliminating or weakening the conditions that drive the balancing loop, we eliminate the limiting factor that slows down the performance of the system (Kim and Lannon 1997, Kim and Anderson 1998). Hence, it is important to focus on sustainably increasing agricultural productivity.

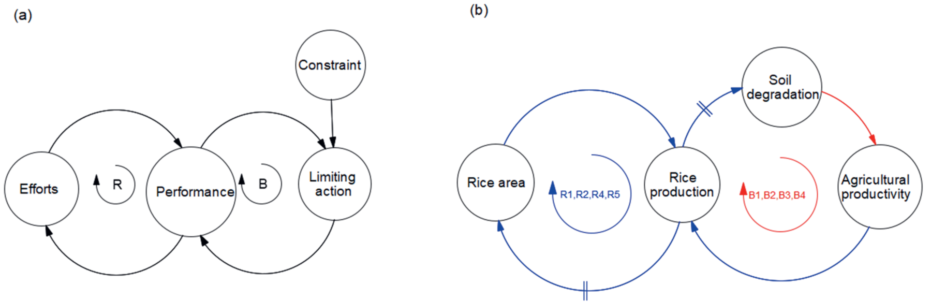


Figure 4.6. Limit to success archetype (a) structure pattern template. (b) Reinforcing loops R1, R2, R4 and R5 are efforts to increase rice production through rice area expansion. On the other hand, balancing loops B1, B2, B3 and B4 limit the growth in rice production because of low agricultural productivity constrained by soil degradation.

One way to achieve an increase in agricultural productivity is through mechanisation. In our system, mechanisation acts through three feedback loops (R3, R4 and B3, Figure 4.4). These loops work through mechanisation to increase rice area (R4, B3) or agricultural productivity (R3). However, rice area expansion leads to soil degradation which limits agricultural productivity. Mechanisation can enable or constrain sustainable rice production. The ambiguity of mechanisation as an enabler or deterrent of sustainable crop production has been highlighted in the literature, especially for African farms that are the least mechanised globally (Sims et al. 2016, Daum and Birner 2020). Further contextual studies are therefore needed to assess the outcomes associated with mechanisation. For example, Takeshima (2020) assessed the effects of mechanisation and related technologies on the economies of scope between rice and non-rice crops in

Nigeria. They found that between rice and non-rice crops, there were more benefits to mechanisation thereby increasing agricultural productivity but between non-rice crops only, there were less benefits.

In our FCM, mechanisation is also influenced by government investment through financing and subsidisation programmes (Financing and subsidisation → Mechanisation). Another pathway is the diversion of public and private foreign exchange funds previously towards rice imports but now towards agricultural investments in mechanisation (Government import restriction policies → Local economic growth → Mechanisation). These interacting mechanisms demonstrate food import substitution which has been successful in creating positive growth in agricultural production in some countries (Kurbatova et al. 2020, Podoba et al. 2020). However, while there is potential success of food import substitution in increasing rice agricultural development, further studies should investigate the potential trade-offs with food security within the context of Nigeria's rice agri-food system.

Fixes that fail (expanding rice area fails to increase production due to low productivity)

The fixes that fail archetype occurs when a quick fix solution is implemented to address a problem symptom, but it only temporarily alleviates the problem and has unintended consequences in the long term (Figure 4.7) (Kim and Anderson 1998). In Nigeria's rice agri-food system, the absence of imported alternatives has increased the demand for local rice. In response to this rice demand, farmers increase rice area but soil degradation occurs, leading to low agricultural productivity and perpetuating a cycle of balancing feedback loops (B1, B2, B3, B4, Figure 4.4). Several studies have highlighted the problem of soil degradation in Nigeria as limiting agricultural productivity (Liverpool-Tasie and Takeshima 2013, Olasehinde et al. 2022). Soil degradation is widespread in Nigeria due to agricultural expansion and shorter fallow periods (Onyeiwu et al. 2011, Adenle and Ifejika Speranza 2020). Soil degradation on African arable lands due to low-productivity and agricultural expansion has been reported (Osumanu et al. 2016, Prăvălie et al. 2021, Jagustović et al. 2021).

Historically rice yields have been low in Nigeria (Figure 4.1). This low yield trend is also demonstrated in the FCM dynamics. In the current system (scenario A), the concept agricultural productivity stabilises at a low value (-0.46) whereas the rice area at 7.20 (Figure 4.5). This pattern of declining agricultural productivity persists in all scenarios (Figure 4.5).

To address this issue, a transition is necessary from the current trend of 'low yields, more area expansion' to 'increasing yields, slow area expansion'. According to our results, priority should be given to solutions that improve agricultural productivity, such as improved farm technology, irrigation facilities, fertiliser use and mechanisation.

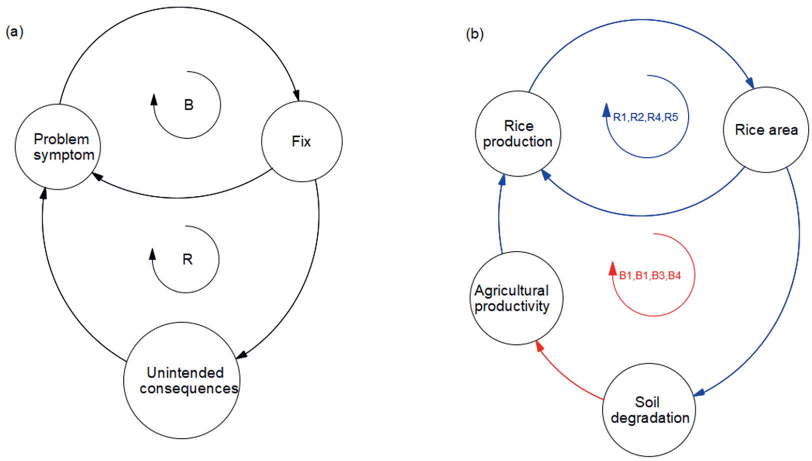


Figure 4.7. Fixes that fail archetype (a) structure pattern template. (b) Reinforcing loops R1, R2, R4 and R5 are efforts to increase rice production through rice area expansion, in response to increased demand for local rice. Balancing loops B1, B2, B3 and B4 represent the unintended consequences of soil degradation due to rice area expansion.

Drifting goals (government import restriction policies creates more food insecurity)

The drifting goals archetype posits that there is a gap between the current state of a system and a desired state and goal of a system (Figure 4.8) (Kim and Lannon 1997, Kim and Anderson 1998). The gap can be bridged by removing the goal, lowering the goal or taking corrective action. We identify the drifting goals system archetype from our FCM dynamics under different scenarios (Figure 4.5). In the current system, the Government prioritises the goal of increased rice production through import restriction policies and investment in agriculture through financing and subsidisation programmes. However, in scenarios C and D, when the drivers - government import restriction policies (C1) and financing and subsidisation (C2) are 'lowered', the system moves to undesirable states (Figure 4.5). As a result, scenarios C and D show lower demand for local rice and less rice production than scenarios A and B. The radically different equilibria between the current state of the system (scenario A) and scenarios C and D can be linked to the theories of stability landscapes (Walker et al. 2004), which reflects that the system is not resilient but rather vulnerable to change (Folke 2006, Adger 2006).

Nigeria's rice import restrictions and agricultural financing policies have been inconsistent, leading to instability in food supplies (Oyejide et al. 2013, Onyiriuba et al. 2020). Other undesirable outcomes often accompany such inconsistencies. For example, increased rice import dependency followed the post-ban period of the mid-1990s, undermining import restrictions' gains (Mendez-del-Villar and Lançon 2015).

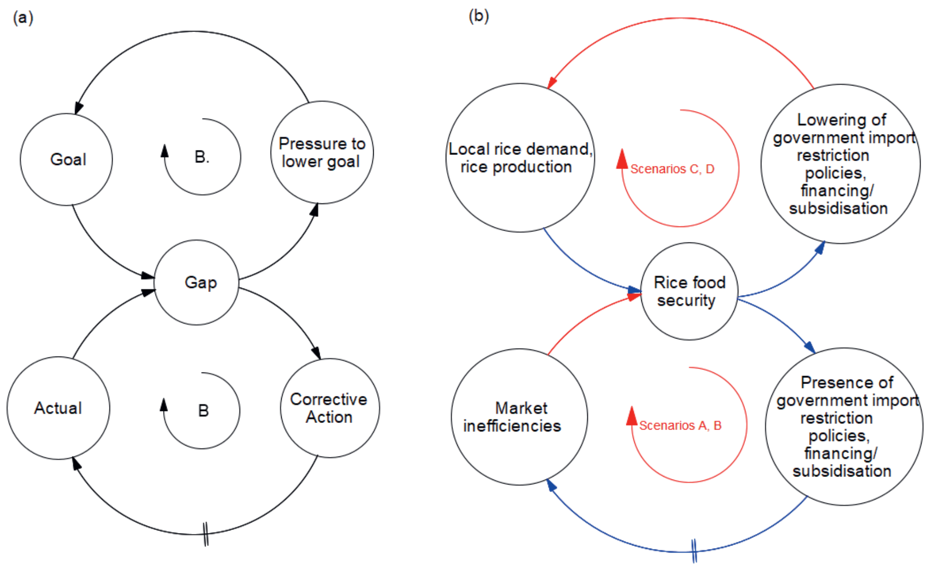


Figure 4.8. Drifting goals archetype (a) structure pattern template. (b) Government efforts to increase rice food security lead to market inefficiencies. However, system-dampening dynamics result from 'lowering' government import restriction policies and financing/subsidisation (see Scenarios C, D, Figure 4.5).

According to our results, the government's import restrictions have created a scarcity of imported rice, leading to higher demand for local rice. However, this results in higher market prices of local rice (Government import restriction policies → Demand for local rice → Market price of local rice). High production costs additionally increase the market price of local rice, making local rice less affordable and leading to food insecurity (Production cost → Market price of local rice). The demand elasticity of price determines the price response in the rice market and is affected by scarcity, as noted in the literature (Marshall 2009, Naylor and Falcon 2010, Clapp and Moseley 2020). Hence, the market protectionist measures by the government lead to market inefficiencies.

To address these risks, following the dynamic theory and strategies embedded in the drifting goals archetype (Kim (1995), Table 4.1), we propose that the government adjusts their self-sufficiency goals and rather develop effective policies that ensure stable and affordable rice supply while developing rice agriculture (Pingali et al. 2005). The government can provide temporary corrective measures such as micro-level interventions (e.g. social safety nets, cash-based transfers, food access-based approaches and food supply-based approaches) to protect vulnerable groups (Rogers and Coates 2002). Offering price volatility buffers can safeguard poor consumers from market inefficiencies (Lombardozzi and Djanibekov 2021). Further research should develop a comprehensive approach that evaluates the time delay between the current state of the system and the target objectives and propose an efficient transition plan.

4.3.2 Reflection on the analytical framework

In their recent article, Piemontese et al. (2022) propose six dimensions for validating archetypes – conceptual, construct, internal, external, empirical and application validity. We reflect on these dimensions and highlight how we considered these in validating the archetypes. Conceptual validity refers to problem framing (Piemontese et al. 2022). Problem definition is the most important step in modelling a system and gives purpose to the modelling process (Sterman 2000). We elicited stakeholders' knowledge by discussing the current societal problems of rice demand and supply using the interview questions as a guide (Supplementary material, Table SM3.1) rather than engaging in a structured interview process. We constructed an FCM based on this knowledge, allowing stakeholders to co-produce a model of Nigeria's rice agri-food system without requiring systems thinking or technical skills.

Stakeholder knowledge played a critical role in selecting the attributes, such as concepts and connections, that form the foundation of our map and model. However, we acknowledge potential biases when the number and type of stakeholders involved are limited, which could result in an incomplete understanding of the system's complexity. Therefore, we took several measures to mitigate these potential biases, including engaging stakeholders from various backgrounds, those affected by the problem and those influencing the system (Gramberger et al. 2015). Additionally, two rounds of feedback involving stakeholders, as well as validation from scientific literature (Alizadeh and Jetter 2017), ensured the model's internal consistency with empirically established relationships and the construct validity of our archetypes. We also combined individual stakeholders' knowledge into one FCM to minimise the impact of individual perceptions (Gray et al. 2015). Adopting these measures provided a comprehensive and contextually relevant system description (Edwards and Kok 2021).

External validity in archetype analysis refers to the extent to which the results are generalisable (Piemontese et al. 2022). Using scientific literature to establish concept names while aggregating stakeholder knowledge also provided external validity to our analysis (Alizadeh and Jetter 2017). We used generalised terminologies in concept naming, allowing cross-comparison with other countries in similar conditions.

In archetype analysis, internal validity concerns how well the chosen approach fits the study context. We chose fuzzy cognitive mapping over causal-loop diagrams because the former allowed for the inclusion of stakeholder knowledge in the quantitative analysis of the system (Kok 2009). The sensitivity analysis conducted on the FCM ensured the internal validity of fuzzy cognitive mapping. Fuzzy cognitive mapping and system archetypes served as system analysis thinking tools to understand the structure and behaviour of Nigeria's agri-food system. Our results confirm the complementarity and applicability of both tools for system analysis.

For empirical validity, our archetypes align with sustainability outcomes and have credible causal mechanisms. The feedback loops and causal mechanisms, matched with generic system archetypes, portray unsustainable and undesirable problem symptoms in a system. Our study directly demonstrates these problem symptoms and proposes ways to increase sustainability outcomes. Finally, applicability validity is important in sustainability research, as it concerns the relevance of findings for decision-making and policymaking. For each archetype, we proposed strategies for the system to achieve desirable outcomes. Through stakeholder involvement, our study incorporated locally significant knowledge that enhances its suitability for guiding national policies.

4.4 Conclusions

Our study acknowledged the complexity of Nigeria's rice agri-food system in ensuring rice food security in a sustainable manner. The structure and behaviour of the system were described through fuzzy cognitive mapping and further analysed using system archetypes (Figure 4.2). In addition to the causal mechanisms depicted in the FCM, fuzzy cognitive mapping offers dynamic modelling of the system, allowing system archetypes to be identified through the dynamics of the system and not only through the system structure. The dynamic modelling allowed for sensitivity analysis of the system and scenario analysis providing additional insights into the system. Through this approach, we identified three system archetypes in Nigeria's rice agri-food system – limits to success, fixes that fail and drifting goals. The government's priority on increasing rice production drives demand for local rice through import restriction policies. In addition, the government supports local rice production through financing and subsidisation programmes. In response, farmers' conversion of arable land to rice area increases. However, this rice area expansion results in soil degradation and low productivity which limits rice production (limits to success archetype). Our results corroborated with other studies to show that mechanisation can increase agricultural productivity but can also lead to unsustainable rice production. However, further studies should investigate the strategies and conditions to maximise mechanisation to increase rice production sustainably.

As highlighted, farmers tend to increase rice area as a 'quick fix' to productivity problems, which leads to unintended consequences such as soil degradation (fixes that fail archetype). Soil degradation further decreases agricultural productivity and necessitates further rice area expansion. Therefore, farmers are trapped in a cycle of rice area expansion – soil degradation – reduced agricultural productivity. In addition to mechanisation mentioned in the previous paragraph as a solution to the limit-to-success archetype, improved farm technology, irrigation facilities and fertilisers directly increase agricultural productivity and, thus, should be the target concepts to be improved the system as long-term fixes of the problem of agricultural productivity.

Due to the unmet demand for local rice generated by the import-restriction policies, the government could be pressured to lower the goal of self-sufficiency (drifting goals archetype). However, from our analysis, suspending import-restriction policies altogether leads to undesirable system states with less demand for local rice and less rice production. Therefore, we propose that the Government adjusts the self-sufficiency goals to ensure a stable rice supply, considering the time delay it may take for local rice production to meet rice demand. Also, poor consumers should be provided temporary micro-level interventions such as price volatility buffers.

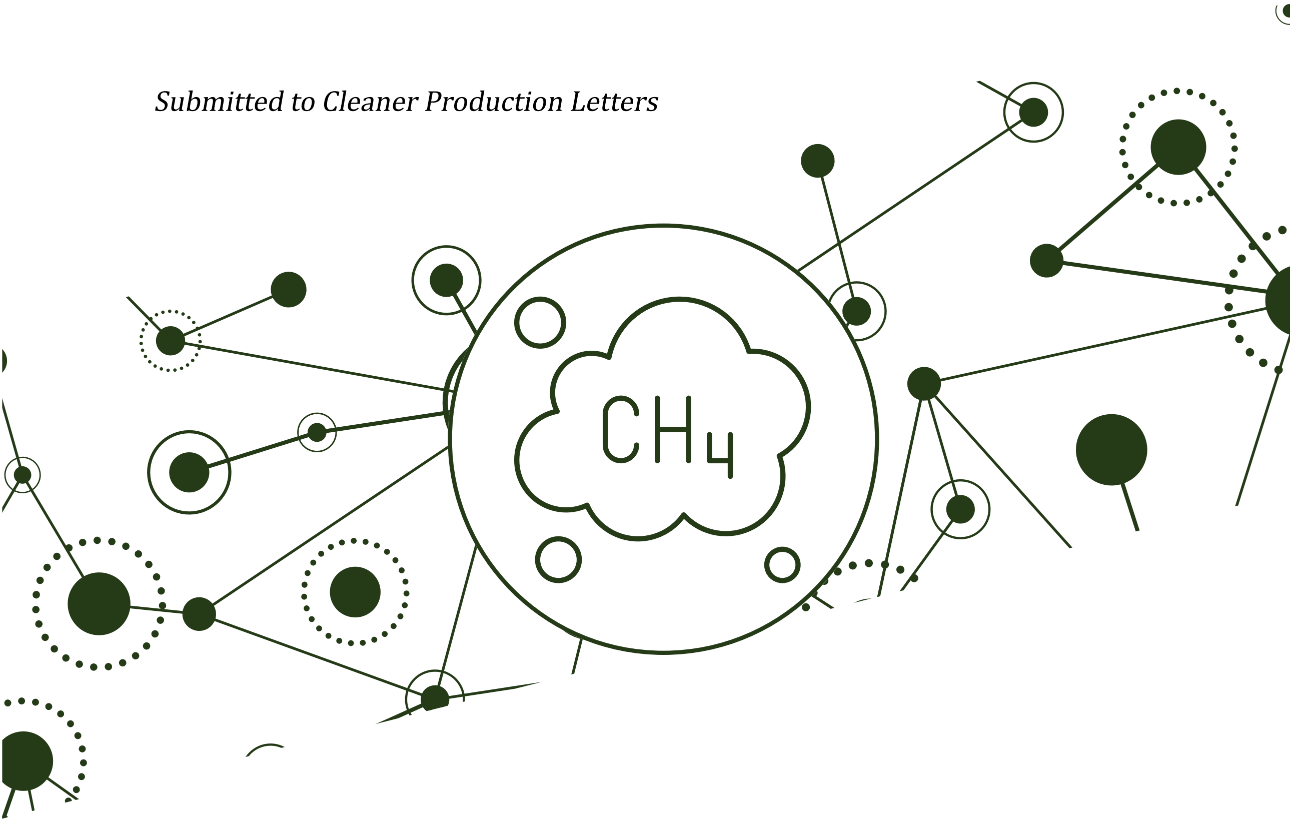
The archetypes we have identified provide a valuable starting point for future research to improve Nigeria's rice agri-food system. Our study underscores the importance of government policies in promoting food security and sustainability while offering solutions to longstanding issues such as soil degradation, low agricultural productivity and market inefficiencies.

Chapter 5

Assessing land use and management scenarios to quantify GHG emissions in Vietnam: Application of the iCLUE Model and SECTOR Tool

Edwards G. I., Kok, K., van Eupen, M., Bui, Y., Sander, B.O. Assessing land use and management scenarios to quantify GHG emissions in Vietnam: Application of the iCLUE Model and SECTOR Tool.

Submitted to Cleaner Production Letters



Abstract

The Agricultural and Forestry sector (AFOLU) contributes significantly to global greenhouse gas (GHG) emissions but also offers opportunities for mitigation and carbon sequestration. Rice cultivation, a major source of GHGs in Asia, has received attention in national GHG inventories. Various complex models have been used to estimate GHG emissions. However, simpler models are more suitable for country-level estimates. Our study applies two models - the Conversion of Land-use and its Effects (iCLUE) model for spatial land allocation and the Source-selective and Emission-adjusted GHG CalculaTOR for cropland (SECTOR) model to estimate GHG emission intensities under different conditions. The iCLUE and SECTOR models provide cost-effective and user-friendly approaches for national inventory reporting. In our study, scenario narratives derived from expert consultations were converted to quantitative land use demands assigned different emission intensities based on management practices and zone-specific factors. The study compares conventional and sustainable rice management practices and thus demonstrates the effects of sustainable land management practices on climate change mitigation. The study also highlights the potential of the AFOLU sector to become a carbon sink, facilitating the development of effective strategies for mitigation and sustainable land use practices.

5.1 Introduction

The Agricultural and Forestry sector, also known as Agriculture, Forestry and Other Land-use (AFOLU) sector is responsible for a quarter of global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change, IPCC 2022). At the same time, AFOLU can also be a sink (removal) for GHG emissions, offering ample opportunities to mitigate GHG emissions, increase carbon sequestration and limit global warming (Clark et al. 2020).

The major greenhouse gases (GHGs) from the AFOLU sector are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In Asia, with the highest share of global AFOLU-related emissions (Pradhan et al. 2019), rice cultivation is among the main AFOLU emission sources (Roe et al. 2021). Flooded rice fields are a significant source of (CH_4) due to the anaerobic conditions (Tubiello et al. 2013).

The world's top ten rice-producing countries, except Brazil, are in Asia (FAOSTAT 2022), making mitigating rice land-based GHG emissions in Asia critical. Because of its key role in GHG emissions, rice has received much attention in National GHG inventories in Asian countries. GHG emissions from rice cultivation are determined by spatial and temporal conditions and management practices (Vo et al. 2020). As such, a better assessment of these conditions advances knowledge on GHG emission intensities from rice cultivation to increase the accuracy of emissions from rice fields and improve national GHG inventories.

Different models have been applied to estimate CH_4 emissions and assess mitigation potentials for rice cultivation. Some examples are the Daily Century (DAYCENT) (Beach et al. 2015) and DeNitrification–DeComposition (DNDC) (Beach et al. 2015, Hwang et al. 2021), Agriculture Forestry and Other Land use Bottom-up model (AFOLU-B model) (Hoa et al. 2014, Hasegawa and Matsuoka 2015, Jilani et al. 2015, Pradhan et al. 2019), Soil and Water Assessment Tool (SWAT) (Gassman et al. 2022) and Estimating Carbon in Organic Soils - Sequestration and Emissions model (ECOSSE) (Begum et al. 2019, Kuhnert et al. 2020). These models are mostly complex requiring high-resolution data for biogeochemical processes and programming expertise of the user (Del Grosso et al. 2012, Hwang et al. 2021).

Simpler models, which require less data and are less technical, are better suited for country-level estimates (Wang et al. 2018). Simpler models generally are easier to implement and require fewer input parameters and data, making them user-friendly (Olander et al. 2013). Moreover, the biogeochemical models such as the DNDC are unable to predict future GHG emissions, do not adequately address and simulate scenarios of land use change and do not work with geophysical information system (GIS) to provide more comprehensive and accurate spatially explicit scenarios (Gilhespy et al. 2014, Min et al. 2017).

Our study applies two models and demonstrates their capacity to solve the aforementioned issues. The two models are the Conversion of Land-use and its Effects (iCLUE) model for spatial land allocation (Verweij et al. 2018) and the Source-selective and Emission-adjusted GHG CalculaTOR for cropland (SECTOR) model (Wassmann et al. 2019) to estimate GHG emission intensities under different conditions. iCLUE is a simple, empirical simulation model using land use demands that can be derived empirically and considering drivers of land use change at the national level (Verburg et al. 2004). The iCLUE model can be applied for scenario analysis quantifying GHG emissions from future land use change, thus contributing to land use planning (Verweij et al. 2018).

The specific objectives of our study are to demonstrate the application of user-friendly models that allow for spatially explicit changes in GHG emissions to be quantified at national level; to demonstrate the inclusion of expert knowledge in scenario development which translates to modelling outputs, and to quantify the influence of different spatial, temporal and management conditions on rice GHG emissions.

5.2 Materials and Methods

5.2.1 Site description

Vietnam is located in South East Asia, with China bordering the North, Laos and Cambodia to the west and the South China Sea to the East. The country is divided into the North, Central and South zones, with rice production concentrated along the long coastline; and in the South in the Mekong Delta and the North in the Red River Delta (Figure 5.1)

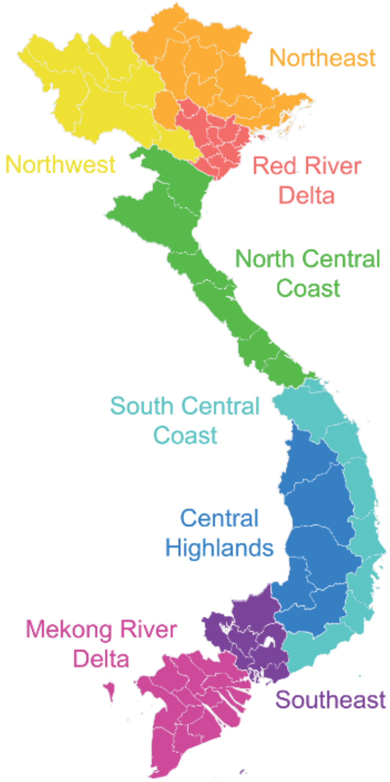


Figure 5.1 Labelled map of the regions in Vietnam classified by the General Statistics Office of Vietnam (used under the Creative Commons licence (CC BY-SA 4.0)

Vietnam lies in the Northern Hemisphere and is influenced by the East Asian and South Asian monsoons (Nguyen et al. 2014). Vietnam's long coastline makes it highly susceptible to wave and tidal amplification, fluvial flooding, storm surges and saline intrusion (Rutten et al. 2014, Eslami et al. 2019). In addition, several major drought events have hit the coastline over the last decades leading to salt intrusion and a shortage of freshwater for irrigation (Guo et al. 2017). These climate-change impacts negatively affect rice land and impede agricultural productivity (Wassmann et al. 2004, Le et al.

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2018). In addition to climate change, water management infrastructure, especially in the Vietnamese Mekong Delta, has affected the hydrological regime, affecting land cover and land use (Le et al. 2018).

In 2020, Vietnam was the fifth largest rice producer in the world (FAOSTAT 2022). Globally, Vietnam is the third highest emitter of GHG from rice cultivation. Rice cultivations contributed the highest net emission (49 ktCO_2e) while forest land contributed the highest net removals (-55 ktCO_2e) to Vietnam's total net AFOLU emissions in 2016 of 44 ktCO_2e (14% of total national emissions) (Figure 5.2). Comparing Vietnam's reported AFOLU emissions of 2016 with those of 2010 and 2014 (MONRE 2020), emissions from rice cultivations are decreasing, albeit rice cultivations still accounts for up to half of the total AFOLU emissions negating the carbon sequestration potential of forests. Accordingly, the government of Vietnam seeks to reduce national GHG emissions through the rice sector by implementing sustainable management practices (MONRE 2020).

5.2.2 Models description

The iCLUE model is an empirical bottom-up simulation allocation model from the CLUE model family (Verweij et al. 2018). The iCLUE model uses empirically derived relations between land-use change and driving forces (Verweij et al. 2018). iCLUE employs various criteria to distribute land use based on specific land use demands effectively. The allocation process considers factors such as land suitability, conversion rules and land use demand on each land use class. Conversion rules establish limitations on land use changes, such as prohibiting urban areas from converting into pastureland or setting specific timeframes for harvesting new production forests. The projected area demands specific land use types to inform the allocation, ensuring that it aligns with scenario-based assumptions (the conversion rules and spatial restrictions for our study are presented in the Supplementary material Table 5.1). By integrating these considerations, CLUE calculates spatial land allocation determined by socio-economic and biophysical changes (Verweij et al. 2018). The land use demands for the iCLUE model can be derived empirically, considering specific processes and mechanisms that drive land use change at the national level. By doing so, the iCLUE model can inform sustainable land management, quantify carbon stock from land use change and support future land use planning (Verweij et al. 2018).

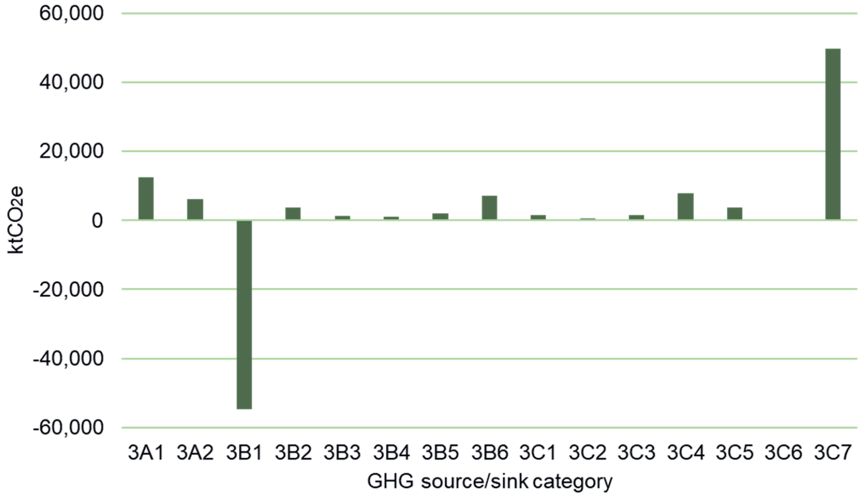

Figure 5.2 GHG source/sink categories and associated emissions of the AFOLU sector 2016. Source: Vietnam 2016 National Inventory Records (MONRE 2020). Codes on the x-axis represent the following GHG source/sink category from the IPCC. 3A1- Enteric fermentation, 3A2 –Manure management, 3B1 – Forest land, 3B2- Cropland, 3B3- Grassland, 3B4 – Wetlands, 3B5- Settlements, 3B6 – Other land, 3C1- Emissions from biomass burning, 3C2 – Liming, 3C3 –Urea application, 3C4 – Direct N_20 emissions from managed soils, 3C5 – Indirect N_20 emissions from managed soils, 3C6 – Indirect N_20 emissions from manure management, 3C7 – Rice cultivation.

The SECTOR tool is a simple spreadsheet-based model that calculates rice emission intensities based on several emission factors that differ by location, zone and management practices (Wassmann et al. 2019). The input parameters of SECTOR are subdivided into pre-season, within-season and end-season management practices. In addition, there are emission and scaling factors for conventional practices and several sustainable practices such as alternate-wetting-and-drying (AWD) and the Sustainable Rice Platform (SRP) practices (Sander et al. 2015). The SECTOR tool requires little technical knowledge and can be adapted to suit any user (Wassmann et al. 2019).

5.2.3 Model input data

This section presents the details of our emissions quantification methodology. We followed the IPCC Good Practice Guidance for Land use, Land-use Change and Forestry

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to estimate GHG emissions from land-use sources and sinks (IPCC 2003). We considered two factors to estimate GHG emissions: Activity data (area of land use change (ha) and emission intensities ($tCO2_e$ ha^{-1}) (Figure 5.3).

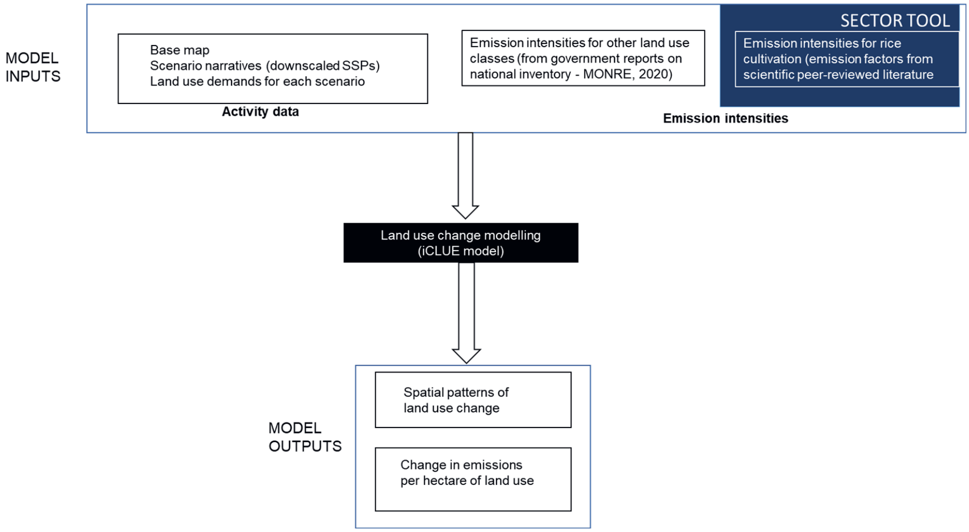

Figure 5.3 Process of the land use change modelling

Activity data

Base map: Land use and cover were classified based on a high-resolution land-use map from Hoang et al. (2020) (250m * 250m) and the Copernicus Global Land Service map (Buchhorn et al. 2020) (100m * 100m). Both maps were developed using a comprehensive mapping approach which allows the classification of forests, rice and cropland. The Vietnam Ministry of Natural Resources and Environment land-use categories used in the national inventory report (MONRE 2020) differ from the maps of Hoang et al. (2020) and Buchhorn et al. (2020). We compared these classifications and reclassified Vietnam's land use into one map which represented the baseline scenario (Figure 5.4).

Scenarios for Vietnam land use: We developed four land-use scenarios starting with the Shared Socio-economic Pathways (SSPs). The SSPs describe the global socio-economic, technological, institutional and environmental developments by 2100 (O'Neill et al. 2017) and reflect future challenges to climate change mitigation and adaptation (van

Vuuren et al. 2012). We refer to the global SSP narrative descriptions (O'Neill et al. 2017, Popp et al. 2017, Riahi et al. 2017). Narratives of the SSPs have been developed for, among others, Europe (Kok et al. 2019), Central Asia (Pedde et al. 2019, Nunez et al. 2020) and West Africa (Palazzo et al. 2017). Most of these regional SSPs are until 2050. Likewise, in this study, we develop narratives for Vietnam's AFOLU sector until 2050, focusing on rice cultivation. To downscale the SSP narratives from global to national scale, we consulted with eight rice experts from Vietnam to capture the local dynamics of land use observed (the experts' profiles are provided in the Supplementary material Table SM5.2).

The scenario narratives need to be converted to quantitative land use demands. Data from the Global Agro-Ecological Zoning version 4 (FAO and IIASA 2022) was used to estimate rice yields and production under different scenarios from which the rice land required by 2050 is then calculated. The percentage change in future rice yield under different climate scenarios – Representative Concentration Pathways (RCP) 2.6 and 8.5 were used. The relevant radiative forcing levels for the Paris Agreement are 2.6 W/m^2 leading to warming well below 2 °C and 1.9 W/m^2 limiting warming to 1.5 °C or below (IPCC 2018). Both radiative forcing levels are captured by RCP2.6 whereas RCP8.5 represents a high-end emission pathway.

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The data for the corresponding yield changes for RCP2.6 was obtained from the country profile for Vietnam in the GAEZ (FAO and IIASA 2022). Under RCP2.6, rice yields will increase by 1.4% whereas under RCP8.5 will decrease by -3.2% in all agroecological zones in Vietnam from 2040-2070 (2050s) compared to historical yields. We used a yield change rounded to 3% and 1% to represent a decrease or increase in yields for different SSPs, assuming different climates for different SSPs. We assume that under SSP 1, yield increases by 3% and rice production decreases by 3%. SSP 3 – yield decreases by 3% and production is maintained at the current value. SSP 4 - yield decreases by 3% and production slightly decreases by 1%. SSP5 – production is maintained and yield increases at 3%. In order of rice area, we have SSP 3 > SSP4 > SSP5 > SSP1. Other land use classes were assigned quantitative land use demands informed by the knowledge gathered from the expert consultation.

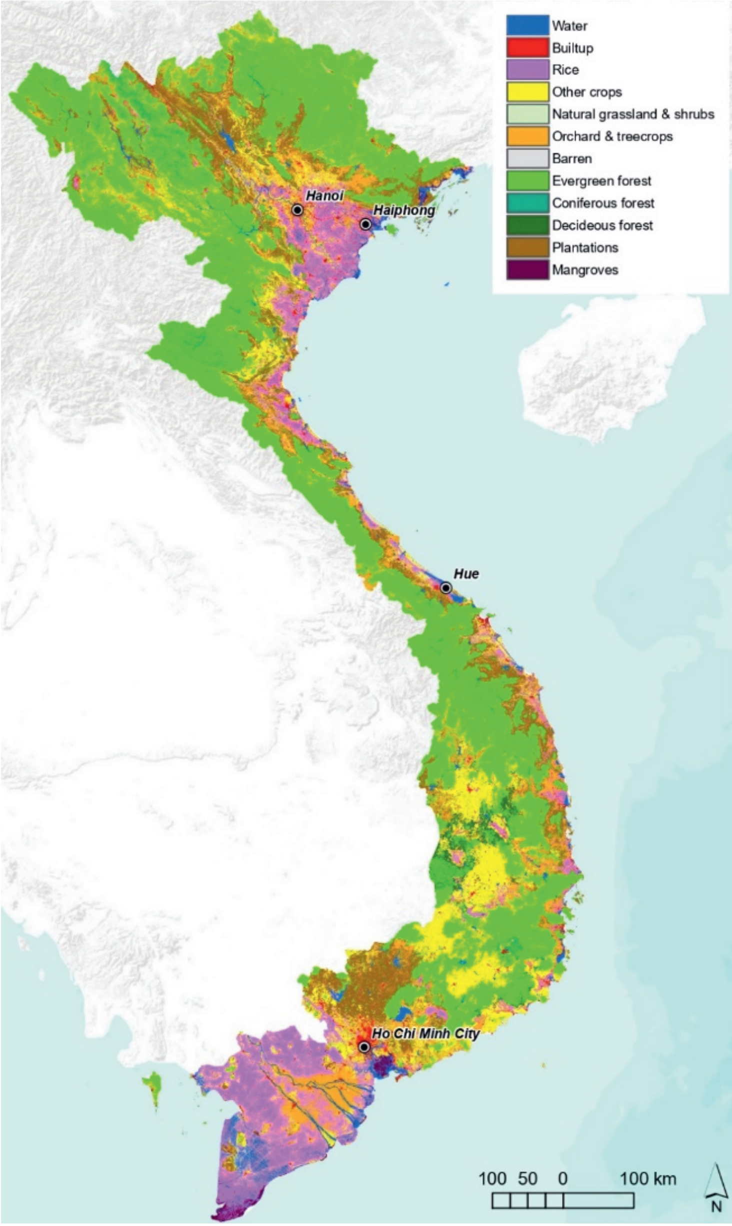

Figure 5.4 Base map of Vietnam from reclassified maps showing land use classes

Emissions intensities

Estimating emissions intensity for land use classes: The IPCC guidelines provide different tiers representing methodological complexity in estimating emissions or removals from land use (IPCC 2014). Tier 1 is based on default assumptions, Tier 2 is similar to Tier 1 but based on country-specific parameters and Tier 3 is based on process-based or empirical models to estimate GHG emissions (IPCC 2014).

We used the Tier 1 approach for all land classes except rice cultivations. For Tier 1 and 2, it is assumed that forest soil C stocks do not change with management. Therefore we did not classify forests into various types, management classes or natural disturbance regimes (IPCC 2006). Instead, we assigned the same emission intensity for all forest classes – evergreen forest, coniferous forest, deciduous forest, plantations and mangroves. Similarly, we did not include soil emissions.

Figure 5.2 shows the GHG emissions/removal for 2016 reported in the National Inventory Records (MONRE 2020). For our study, we considered two categories under the AFOLU sector - category 3B (3B1 – 3B6) and category 3C7. Category 3B is categorised as 'Land-use, Land-Use Change and Forestry' including forest land, cropland/orchards, grassland, wetlands, settlements and barren land. The target GHG in this category is Carbondioxide (CO_2).

Category 3C are emissions from rice cultivations treated separately under Aggregate Sources and Non-CO_2 Emissions Sources on Land (category 3C). The target GHG in this category is methane (CH_4).

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We derived the emissions intensities from the historical emissions data by dividing the total emissions for each land use change by the reported area (see Supplementary material SM5.3 for calculation details). The records provide emissions for land remaining in a land use category and land converted to land use. Estimating emissions intensity for rice cultivation: The annual amount of CH_4 emitted from a given area of rice field is a function of the emission factor (EF_{ijk}) using the formula (IPCC 2019):

$$CH_4 \text{ rice emissions} = \sum_{i,j,k}(EF_{i,j,k}.\, t_{i,j,k}\, .\, A_{i,j,k}\, .\, 10^{-6}) \quad \text{(Eq. 2)}$$

Where CH_4 rice emissions are the annual methane emissions from rice cultivation in $kgCH_4yr^{-1}$

$EF_{i,j,k}$ = a daily emission factor for i, j and k conditions, kg CH_4 $ha^{-1}day^{-1}$

$t_{i,j,k}$ = cultivation period of rice for i, j and k conditions, day

$A_{i,j,k}$ = annual harvested area of rice for i, j and k conditions, ha yr^{-1}

i, j and *k* = represent different ecosystems, water regimes, types and amounts of organic amendments and other conditions under which CH_4 emissions from rice may vary

Rather than using the global default EFs for methane from rice cultivation, we used country-specific EFs for rice cultivation in Vietnam disaggregated spatially and temporally. There are different EFs for each geographic zone (North, Central and South Vietnam) and different EFs for early, middle and late seasons. We obtained these disaggregated EFs from Vo et al. (2020), which specify zone-specific and season-specific EFs for Vietnam rice cultivation (Table 5.1).

For management practices, we chose the conventional practice (CP) and Sustainable Rice Platform recommended practices (SRP) to represent divergent rice management practices. Conventional practices (CP) refer to 'continuous flooding within the season or uncontrolled flooding is practised in partially irrigated areas, upland areas and areas under rainfed rice production. Residue incorporation is done less than 30 days before the start of the season. Stubbles are left on the field before the season and straw is burned at the end of the season. Sustainable Rice Platform recommended practices (SRP) promote minimal inorganic fertilisation, multiple alternate wetting and drying and no straw burning after the season.

These management practices differ in pre-season and within-season water management (Table 5.1). Our study did not consider end-season management and nitrous oxide emissions since these are not the target emissions in rice cultivations in Vietnam's national inventories. Other factors such as cultivation period are specified in Table 5.1.

We calculated different rice cultivation emission intensities with the SECTOR tool, inputting different emission factors disaggregated by management practice, location (spatial) and season (time). We used an average value of 6 tons/hectare for yield since we already account for yield differences in the SSPs. Supplementary Material Table SM5.4 – 5.5 provides an overview of the calculation tool.

5.3 Results

5.3.1 iCLUE model inputs

Scenario narratives

SSP1: sustainability—taking the green road. The rapid adoption of optimal sustainable rice production standards leads to sustainable yield increases. Emphasis on economic growth shifts toward a broader focus on human well-being. There is less pressure on local natural resources and thus, the restoration of mangroves and other natural forest classes. There is a promotion of 'high-quality rice' cultivated with fewer agrochemicals. As a result, there is a reduction in the rice area and further diversification of farming systems.

SSP3: regional rivalry—a rocky road. Land-use change is hardly regulated. Rice yield and other agricultural yield decrease due to Climate change impacts and saline intrusion Agricultural yields reduce. Built-up area slightly increases partly because of high urbanisation rates while forest ecosystems reduce. Sea level rise leads to loss of land area and increases in areas classified as wetlands/water. Limited transfer of new agricultural technologies leads to poor adaptation to climate change impacts.

SSP4: Inequality— A road divided. Food trade is globalised, but access to markets is limited for poor farmers, increasing their vulnerability. Deforestation is high due to few incentives for avoiding deforestation and afforestation. Yields decrease leading to expansion of agricultural area.

SSP5: Fossil-fuelled development—taking the highway. Deforestation is high. Crop yields are rapidly increasing. Rice production is overall resource and energy intensive. Meat-based diets trigger the expansion of grass/shrubland and cropland for animal husbandry at the expense of natural forest classes. Table 5.2 provides a schematic summary of important differences between scenarios.

Table 5.1: Methane emission factors and season length by geographic zone and season for rice cultivations.

Input parameters in the SECTOR tool		Emission Factor	Conventional practice or Sustainable Rice Practice	Source
Methane EF	North (early season)	2.21	CP, SRP	Vo et al. 2020
	North (middle/late season)	3.89	CP, SRP	Vo et al. 2020
	Central (early season)	2.84	CP, SRP	Vo et al. 2020
	Central (middle/late season)	3.13	CP, SRP	Vo et al. 2020
	South (early season)	1.72	CP, SRP	Vo et al. 2020
	South (middle/late season	3.78	CP, SRP	Vo et al. 2020
Water management	Irrigated- Multiple aeration	0.55	SRP	IPCC 2019
	Irrigated- Continuously flooded	1	CP	IPCC 2019
Residue management	Residue incorporated long (>30 days) before season)	0.19	SRP	IPCC 2019
	Residue incorporated shortly (≤30 days) before season)	1	CP	IPCC 2006
Pre-season treatment	Non-flooded >180 days before season	0.89	SRP	IPCC 2019
	Non-flooded ≤ 180 days before season	1	CP	IPCC 2019
	Flooded > 30 days before season	2.41		IPCC 2019
Cultivation period	North_early season	123 days	CP, SRP	Vo et al. 2020
	North_late	104 days	CP, SRP	Vo et al. 2020
	Central _ early	107 days	CP, SRP	Vo et al. 2020
	Central _ late	107 days	CP, SRP	Vo et al. 2020
	South_ early	101 days	CP, SRP	Vo et al. 2020
	South_ late	99 days	CP, SRP	Vo et al. 2020
Rice yield	Average value	6 tons/ha	CP, SRP	FAOSTAT

Table 5.2 - Differences in trends between scenarios

	Rice Yields	Rice land	Challenges for mitigation	Challenges for adaptation
SSP1	↑	↓	↓	↓
SSP3	↓	↑	↑	↑
SSP4	↓	↓	→	↑
SSP5	↑	↓	↑	↓

Land use demands per scenario

Scenario narratives translate into strongly different land-use demands (Figure 5.5). Forest land is the highest class in all scenarios except SSP3, with marked deforestation and increased water area. In SSP1, forest land is more or less maintained and rice land decreases from 13% to 2%.

Emission intensities

The emission intensities are reported for each land use class differentiated as land remaining in a land use class and land converted to that land use class (Table 5.3). The land remaining in a land-use class has lower emission intensities than land converted from one type to another (Table 5.3). Land converted to forests has the lowest emissions; the negative values demonstrate their carbon sequestration potential.

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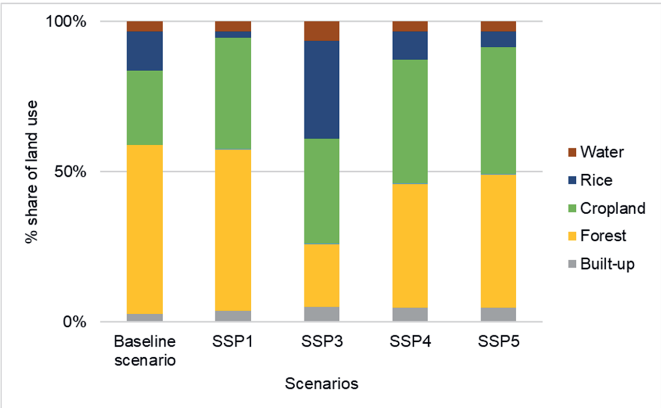

Figure 5.5: Land use demands in the baseline scenario (2020) and the SSPs (2050)

5.3.2 iCLUE model outputs

Projected spatial patterns of land use change

The largest differences in the scenarios are between SSP1 and SSP3. For this reason, we report the findings from these two scenarios henceforth (other results for other scenarios – SSP4 and SSP 5) are reported in Figure SM 5.6 Supplementary Material). The differences are more apparent in the spatial patterns of land use change between the scenarios (Figures 5.6 and 5.7). In SSP1, there is an increase in forest areas all over the country and less rice area. The rice area has been converted back to forest land. The main changes are in the coastline, the Red River Delta and the Mekong Delta. In SSP3, rice land is more widespread in the country. However, the Red River Delta and Mekong Delta remain rice production hubs.

Table 5.3: Emissions intensities for estimating GHG emissions from future land use change. CP - Conventional practice, SRP - Sustainable Rice Practice

Name		$GHGha^{-1}$ ($tCO2_eha^{-1}$)	$GHGcell^{-1}$
Forest	Stable forest	-3.64	-22.74
	Land converted to forests	-4.72	-29.47
Cropland and orchards	Stable cropland and orchards	-0.11	-0.66
	Land converted to cropland and orchards	2.51	15.69
Grass land	Stable grassland	0.00	0.00
	Land converted to grassland	8.15	50.95
Water	Stable water	0.00	0.00
	Land converted to water	5.75	35.91
Built-up	Stable built-up	0.00	0.00
	Land converted to built-up	5.69	35.54
Barren land	Stable barren land	0.00	0.00
	Land converted to barren land	3.55	22.21
Rice	Stable rice or land converted to rice in the North and with CP	18.94	118.38
	Stable rice or land converted to rice in the North and with SRP	9.27	57.94
	Stable rice or land converted to rice in the Central and with CP	17.89	111.81
	Stable rice or land converted to rice in the Central and with SRP	8.76	54.75
	Stable rice or land converted to rice in the South and with CP	13.71	85.69
	Stable rice or land converted to rice in the South and with SRP	6.71	41.94

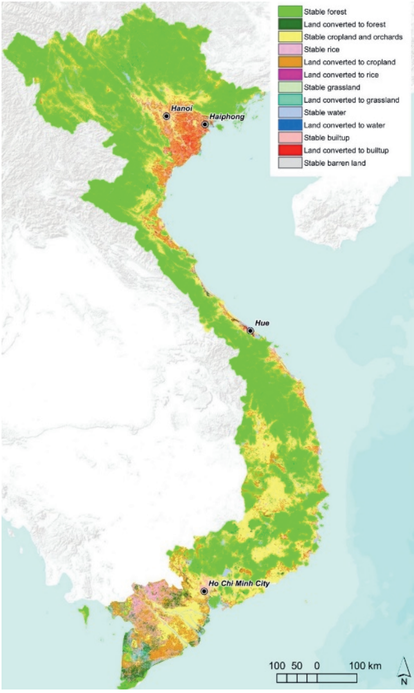

Figure 5.6 Spatial pattern of land use change for SSP1 in 2050

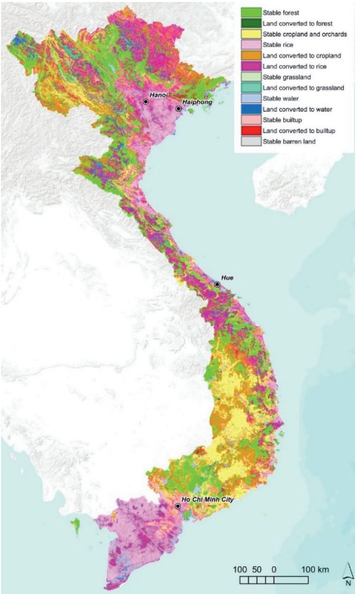

Figure 5.7 Spatial pattern of land use change for SSP3 in 2050

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Total emissions by zones and scenarios

In all scenarios except for SSP3, the Central and North zones have lower GHG emissions than the South (Figure 5.8, also see Figure SM5.6 Supplementary Material). The total emissions in SSP1 for both CP- and SRP-rice management are negative values. Here, land acts as a sink and not a source of GHG emissions (Figure 5.8). The lowest projected emissions across the zones are from SSP1_Central, whereas the highest is from SSP3_North (see Figures 5.10 and 5.11).

Figure 5.8: GHG emissions for SSP1 and SSP3 scenarios by zone (C- central, N-North, S-South) and by management practice - Sustainable rice recommended practices (SRP) and Conventional practices (CP)

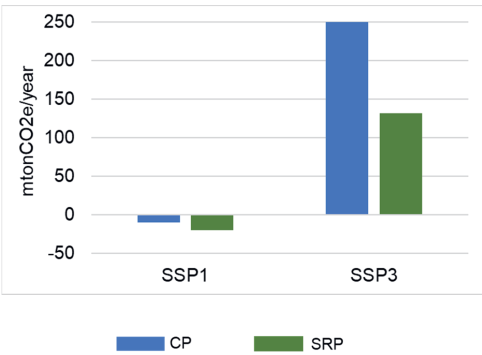

Figure 5.9 The sum of the change in total GHG emissions in SSP1 and SSP3 scenarios by management practice - Sustainable rice recommended practices (SRP) and Conventional practices (CP)

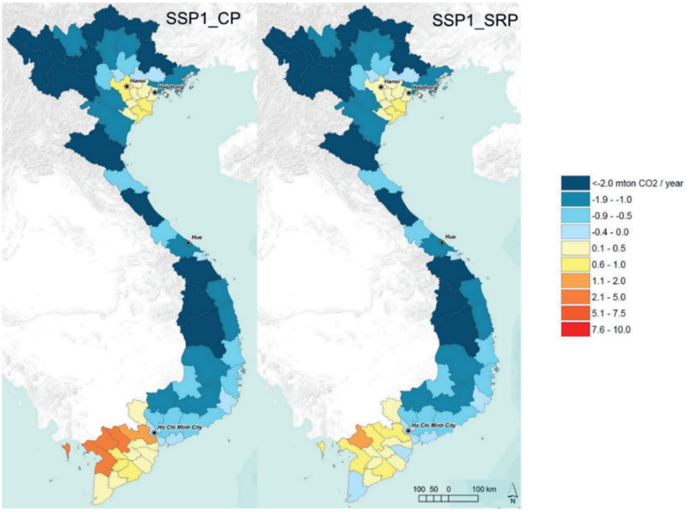

Figure 5.10 Change in GHG emissions for Vietnam in 2050 under Vietnam's SSP1 Conventional practices (CP) and Sustainable rice practices (SRP)

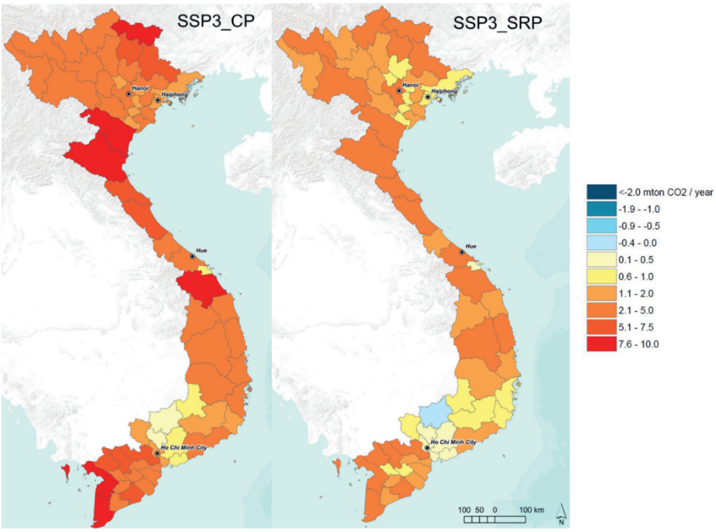

Figure 5.11 Change in GHG emissions for Vietnam in 2050 under Vietnam's SSP3 Conventional practices (CP) and Sustainable rice practices (SRP)

5.4 Discussion

Vietnam's agricultural sector faces multiple sustainability problems and conflicting challenges of achieving food security, economic development, environmental protection, mitigation and adaptation to climate change. These challenges are embedded in land use changes. Our study sought to quantify spatially explicit emissions using the iCLUE model and SECTOR tool.

5.4.1 Scenario narratives

We began with downscaling the SSPs to Vietnam's national level. Downscaling the SSPs increased its applicability to a national level. Through expert consultation, scenario narratives were derived that we converted to quantitative land use demands. Emission intensities for land use change were obtained from literature with those of rice disaggregated by spatial, temporal and management practices. The scenarios, thus, were derived based on the best available science and experts' knowledge increasing its relevance (Mallampalli et al. 2016, Kok et al. 2019).

We assumed in SSP1 that sustainable practices are adopted but simultaneously that rice yields and other crop yields increase. Different studies have presented alternative research results when it comes to sustainable rice practices and rice yield. With AWD, some studies report that yields were maintained or increased depending on soil properties such as pH (Carrijo et al. 2017); on climatic conditions of the area (Sander et al. 2017). The consensus is that rice grain yield does not differ significantly with sustainable practices (Carrijo et al. 2017, Martínez-Eixarch et al. 2021, Zhang et al. 2023). Thus, we assume an SSP1 future with increased rice yields and sustainable management practices.

5.4.2 Emission intensities and land use change

The emission intensities derived for each land use class (Table 5.3) show higher values for the category of land converted to a land use class than the stable classes (land remaining in a land use class). Land use change emits more emissions from clearing, leading to changes in carbon stock (Huang et al. 2023). Therefore, avoiding deforestation has greater potential for GHG sequestration than reforestation. Thus short term actions to prevent deforestation should be pursued alongside afforestation actions in Vietnam.

This is particularly important as Vietnam continues its forest transition. Emission intensities are also higher in conventional practices than in sustainable rice practices, showing the potential for adopting management practices to decrease emissions from rice cultivation.

The largest differences in land use change and emissions were seen between SSP1 and SSP3 so we presented results on these two scenarios. We estimated lower emissions than the baseline scenario in SSP1 and higher emissions in SSP3 (Figure 5.9 - 5.11) (see Supplementary Material Table SM5.4 for calculations). These projections align with the global SSPs for land use futures where SSP3 is the highest and SSP1 the lowest in GHG emissions (Popp et al. 2017).

We conducted two model simulations for each scenario, considering different rice management practices: Sustainable Rice Platform recommended practices (SRP) and conventional practices (CP). In each scenario, we assume a full adoption of SRP or full adoption of CP. However, in reality, these practices are often applied in a mixed manner within a country. Nevertheless, in the future scenario SSP1, sustainable rice management practices are expected to be increasingly adopted, while conventional practices (CP) will be more prevalent in SSP3. By providing greenhouse gas (GHG) estimates for each management practice separately, we can better understand the individual contribution of these practices in mitigating GHG emissions from rice cultivation.

Notably, our study demonstrates the contribution of land use change and management practices to GHG emissions. In SSP1, land acts as a sink rather than a source. This positive outcome can be attributed to avoided deforestation, afforestation and sustainable rice management practices. Vietnam is globally recognised for undergoing a forest transition from net deforestation to net afforestation in the 1990s. Our results demonstrate the impact of sustainable land management practices to mitigate climate change.

We also observed that the emissions differed by zone from highest to lowest for SSP1 (and the other scenarios reported in Figure SM 5.6 Supplementary material) in the order of South>North>Central. Whereas for SSP3, in the order North>Central>South zones. We can attribute the zonal differences between SSPs to the dynamic modelling of the water/wetland area only in SSP3. Climate scenarios for Vietnam project higher temperatures and annual rainfall by 2050 (Dasgupta et al. 2009, World Bank Group and Asian Development Bank 2021) and these temperature and rainfall changes are projected to increase faster in the North than in the Central and South zones (MONRE 2009, Ngo-Duc et al. 2014). The North zone is already known as a hotspot for flooding and storm surges (Giang and Phuong 2018, Giang 2021). Therefore iCLUE's spatial allocation is similar to other projections for water-related climate change impacts.

5.4.3 Limitations of study and recommendations for further study

Although the SECTOR tool outputs are incorporated as part of the iCLUE model input, they are not directly linked. Future studies should focus on advancing the iCLUE model and the SECTOR tool, potentially establishing a dynamic linkage between them. The iCLUE model and the SECTOR tool potentially address the need for cost-effective, feasible and user-friendly approaches for national inventory reporting (Olander et al. 2013). So such dynamic linkage will be beneficial to national governments.

Activity data and emissions intensities were obtained from various sources, likely introducing uncertainty in the data. However, using input data from previous studies and expert consultation lend credibility to the results and make them contextually relevant. On the model side, the CLUE model family are among the most used land use models across many scales. As such, the model has been validated in many studies (such as Kok et al. 2001, Pontius et al. 2008, Verweij et al. 2018).

Our study primarily focused on methane emissions from pre-season and within-season water management in rice cultivation, excluding end-season management and nitrous oxide emissions. Methane is the primary GHG emitted from rice cultivation, but future research could expand the scope to estimate other GHG emissions from other on-farm sources.

5.5 Conclusions

Our study has presented a parsimonious modelling approach to estimate land-based GHG emissions using the iCLUE model and the SECTOR tool. In addition to the previously discussed application of the models, we highlight that the iCLUE model facilitates the inclusion of qualitative scenario narratives in quantitative simulations and enables various impact measurements (Verweij et al. 2018). Likewise, the SECTOR tool is flexible as it allows for the emission factors to be updated and other input data to be determined (Nelson et al. 2022). An increasing number of studies have applied the SECTOR tool not only for emissions quantification but also to test the influence of, for example, fertilisers on yields (Mboyerwa et al. 2022).

Our study advances the application of the SECTOR model by showing how its output can be used in iCLUE to quantify spatially explicit GHG emissions. These modelling tools advance our understanding of the relationship between land management and GHG emissions. Moreover, they facilitate the development of effective strategies for mitigating emissions and promoting sustainable land use practices.

Our study quantified the effects of spatial explicit modelling of GHG emissions and demonstrated the need for better spatial estimates. We showed the potential impact of increasing the sustainability of rice cultivation on GHG emissions mitigation. Additionally, we showed the potential of a country's AFOLU sector to become a carbon sink in the SSP1 scenario. We demonstrated the need to include spatial differentiations in driver factors such as climate, land use change dynamics and management practices. Our study clearly demonstrates that GHG emission estimates are likely to be substantially different between zones at national level. Moreover, this influence differs depending on the scenario that is applied. More studies like ours which use disaggregated emission intensities should be conducted to provide evidence for the adoption and implementation of sustainable management strategies.

Chapter 6

Twenty-five rice research priorities to achieve sustainable rice systems by 2050

Edwards, G.I., Nelson, K., Le C'lech, S., Coast, O. Luu, T., Koichi, F. Kok, K. Twenty-five research priorities to achieve sustainable rice systems by 2050.

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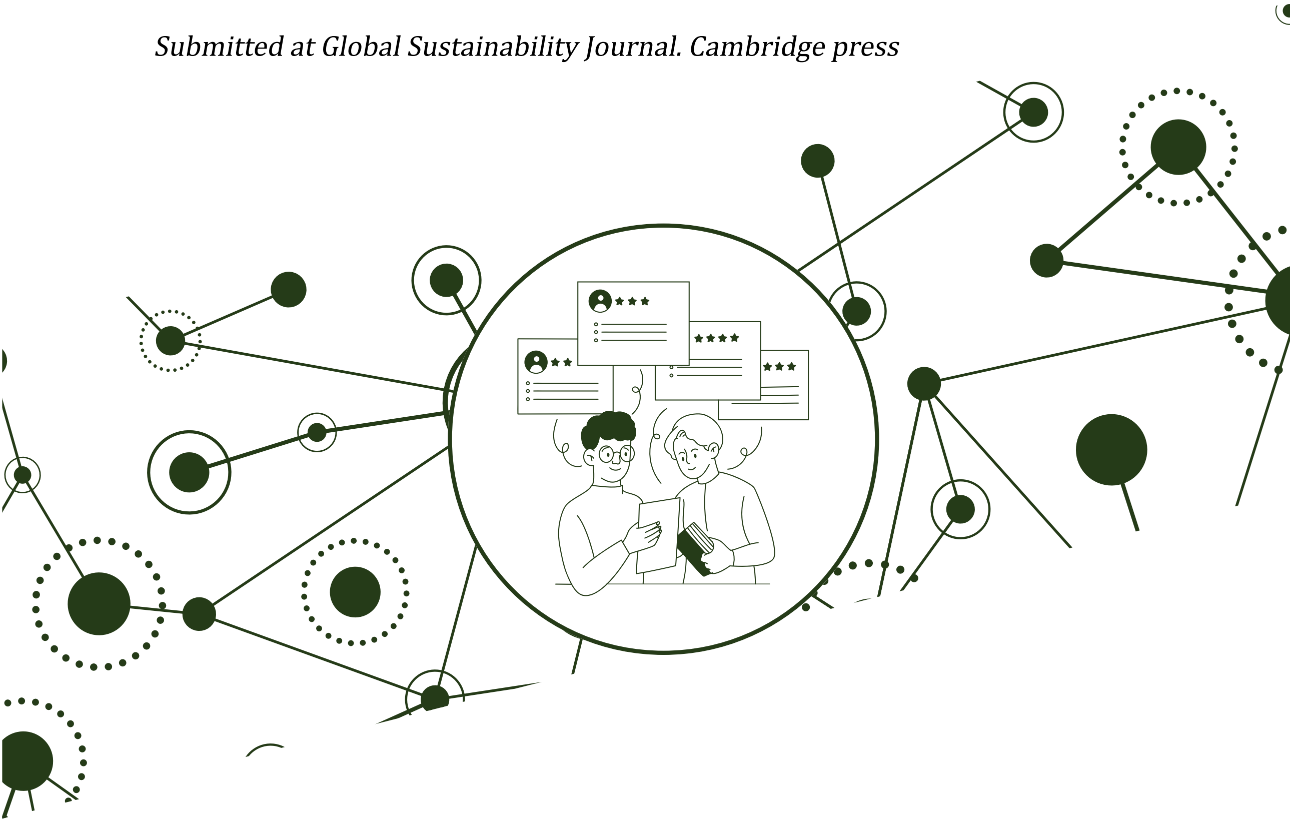


Abstract

Agricultural research and development (AgR&D) is crucial for increasing productivity while preserving natural capital and ensuring sustainable food security. Traditional AgR&D approaches along monodisciplinary lines often have unintended consequences and trade-offs, which can be avoided through integrated and interdisciplinary approaches. One such approach is horizon scanning. We conducted a horizon-scanning activity to identify research gaps to be prioritised for sustainable rice systems by 2050. The horizon scan involved a global and diverse panel of rice experts (101 from across 31 countries) and followed the Delphi Technique. The panel responded to questionnaires on the drivers, projections and research needs for rice AgR&D. Afterwards, research gaps were rated by experts on relevance and novelty. We identified the top 25 research gaps and presented these under four themes: sustainability interactions, agricultural development; genetics, breeding and crop physiology; governance and policies. The research gaps highlight research that needs to be prioritized to achieve sustainable rice systems that enhance resilience, conserve biodiversity and promote socio-economic well-being.

6.1 Introduction

Crop-production systems must increase productivity while preserving natural capital to ensure sustainable global food security (Foley et al. 2011). Agricultural research and development (AgR&D) offer opportunities to achieve this challenging objective (Kristkova et al. 2017). Moreover, AgR&D drives long-term agricultural productivity and innovation with high returns on investments (Alston et al. 2000, Heisey and Fuglie 2007, Alston 2010, Hurley et al. 2014).

Traditionally, AgR&D has addressed most issues along single disciplines leading to unintended consequences and trade-offs. For example, the Green Revolution of the late 1960s led to significant crop yield and food-production increases but also had several negative social-economic and ecological outcomes (Borlaug 2007, Renkow and Byerlee 2010, Stevenson et al. 2013). The Green Revolution primarily benefited large-scale commercial farmers; neglected small-scale farmers and rural communities (Pingali 2012, Gollin et al. 2021, Davis et al. 2022). In addition, the Green Revolution relied heavily on synthetic fertilisers and pesticides and focused on a few high-yielding varieties and crops, resulting in decreased crop diversity, increased vulnerability to pests and diseases and environmental degradation. Hence, while the green revolution was instrumental in averting hunger and generating wealth for many countries, it resulted in fragile agricultural systems (Chand and Haque 1998, Chauhan et al. 2012, Brainerd and Menon 2014, Gupta et al. 2015, Bhatt et al. 2021).

A more integrated and interdisciplinary approach to AgR&D will reduce unintended consequences and trade-offs. Such an approach considers the complex interactions between agriculture, the environment and farming communities. This will lead to sustainable agricultural systems resilient to climate change and promote food security, biodiversity and social, cultural and economic well-being (Sachs et al. 2010, Pingali et al. 2019).

Research gaps must be identified and prioritised by considering research topics, locations and methods (MacMillan and Benton 2014, Pardey et al. 2016). This research-priority setting requires foresight to identify future trends, challenges and opportunities (van Rij 2010). One such foresight activity is horizon scanning, which can anticipate and plan for change (Cuhls 2020). Horizon scanning identifies novel ideas at the margins of current knowledge (Sutherland et al. 2019). It also captures signals of emerging trends with potential future impacts that involve threats and opportunities (Esmail et al. 2020). Horizon scanning in AgR&D can help funding agencies and policymakers identify important research gaps and allow them to allocate resources effectively and efficiently (National Academies of Sciences 2020).

Given the importance of AgR&D and the usefulness of horizon scanning in AgR&D to sustainable agricultural systems, we conducted a horizon-scanning activity with a global and diverse panel of rice-related research experts to identify research gaps that should be prioritised to achieve sustainable rice systems by 2050.

6.2 Rice agriculture and research

Rice research has a long history, which dates to ancient civilisations. For example, early records in China describe seed selection and irrigation to improve rice yields (Anderson 1988). In the 19th and early 20th centuries, scientists began studying rice and improved its productivity through breeding. Later, genetic research heralded the Green Revolution. Increased productivity was the leading research innovation that drove rice-production growth, especially in Asia.

Researchers are nowadays concerned that increases in global (Yuan et al. 2021) and regional rice yields (van Oort et al. 2015) have stabilised and that investment in rice research has stagnated (Zeigler and Barclay 2008, Mohanty et al. 2010). For these reasons, we argue that rice research gaps must be identified and prioritised to achieve increased production, productivity and sustainability in rice systems by 2050. In addition, we highlight the importance of rice below.

First, rice plays an important crop in global food security. Rice is a staple food for over half of the world's population and is grown in more than 150 countries (Seck et al. 2012, Brooks and Place 2019). Rice production needs to increase to meet increasing global demands (Timmer et al. 2010, Samal et al. 2022). However, rice production systems face many challenges in achieving sustainable growth related to environmental factors (soil quality and water and nutrient availability), national and international policy initiatives, labour scarcity and increased competition for arable land.

Secondly, climate change exacerbates challenges in rice production systems by increasing the intensity and frequency of extreme climatic events such as droughts and floods (Wassmann et al. 2009, Hatfield et al. 2011, Singh et al. 2017). More so, rice is mainly produced by small-holder farmers with limited ability to adapt to climate change (Redfern et al. 2012, Misra 2017, Nyadzi et al. 2019, Ojo and Baiyegunhi 2020, Ho et al. 2022). Climate change also inhibits sustainable management practices. For example, practising alternate wetting and drying, which reduces water use and methane emissions, is determined by climatic conditions (Nelson et al. 2015, Sander et al. 2017).

Thirdly, rice production is affected by climate change but also contributes to climate change through greenhouse gas emissions. Rice contributes more to agricultural greenhouse gas emissions than other major cereals (Linquist et al. 2012, Tubiello et al. 2013). In addition, rice production is often associated with groundwater depletion, soil degradation and widespread biodiversity decline (Brainerd and Menon 2014, Gupta et al. 2015, Bhatt et al. 2021).

6.3 Methods

Our horizon scanning activity followed a Delphi technique with two rounds (Box 6.1) (Rowe and Wright 1999, Mukherjee et al. 2015), involving a global and diverse set of rice experts. One hundred and one experts participated from across thirty-one countries and five continents (Figure 6.1). Experts' experience varied from a decade or less (46%) to more than three decades (11%) (Figure 6.2). Experts identified themselves as researchers (69%), academic/university staff (21%) and directors/consultants (10%) from diverse fields (Figure 6.2).

In Round 1, experts answered open-ended questions on the macro drivers that enable or constrain sustainable rice systems and the research needs. The responses were analysed and classified into seven issues and 54 research gaps that formed the basis of Round 2. Experts from Round 1 were re-invited to participate in Round 2 and 60% participated. In Round 2, experts rated the research gaps on relevance and novelty.

Box 6.1: Horizon scanning method

Horizon scanning seeks expert opinions and explores promising trends (Amanatidou et al. 2012, Cuhls et al. 2015, Hines et al. 2019). When conducted as a participatory study that involves stakeholders or experts, it allows for a cross-fertilisation of ideas, facilitates mutual learning and informs decision-making and the development of viable solutions (Wintle et al., 2020). Furthermore, horizon scanning based on experts' opinions harnesses collective expert knowledge (Duboff, 2007) and thus lends credibility to its results (Könnölä et al. 2012). Horizon scanning can be done with a short-term or long-term focus, depending on its goals (Hines et al. 2019).

Several research areas have adopted horizon scanning as a research priority-setting method. These include conservation issues, which have been conducted annually since 2010 (Sutherland et al. 2019), global agriculture (Pretty et al. 2010), digital agriculture (Fleming et al. 2021; Ingram et al. 2022), food-production systems (Glaros et al. 2022) and sub-domains of plant science (Brown et al. 2016; Neve et al. 2018). However, despite the growing frequency of applying horizon scanning for research priority setting in agriculture, most horizon-scanning activities rely on bibliometric analyses. This does not lead to globally applicable and integrated research priorities addressing key food security and sustainability crops.

Our study followed a Delphi technique to engage with rice experts. This technique typically has two or three rounds of engagement with participants. Participants identify pressing issues in a specific knowledge domain, prioritise and rate them by importance and re-evaluate their ratings based on structured feedback or weighted group discussions. Additional rounds can be included. The Delphi technique has many variants, but all share common characteristics: 1) partial or complete anonymity of experts; 2) iterative participation through surveys, interviews, or workshops; and 3) structured feedback in a statistical summary to the experts between rounds (Rowe & Wright, 2001).

Two rounds of surveys were hosted on Qualtrics (an online survey tool). Each survey was pretested to eliminate errors before publishing on Qualtrics. The published survey was publicised through the professional networks of the study co-authors, corresponding authors of relevant publications in rice research and snowballing sampling techniques.

Relevance ratings for sustainable rice systems had four levels: 'high relevance', 'moderate relevance', 'little relevance' and 'no idea'. High, moderate and little relevance reflects the importance of the research gap to achieve sustainable rice systems, whereas 'no idea' indicated that the issue fell outside the experts' knowledge. Novelty ratings had three levels: 'novel' (available knowledge is limited), 'not novel' (sufficient knowledge exists) and 'new to me' (unfamiliar subject). The questionnaires of Rounds 1 and 2 are provided in the Supplementary material (Table SM6.1 - 6.2).

To analyse the results from Round 2, we assessed the level of agreement among participants. A consensus was reached when half of the participants gave the same rating. If there was no consensus on any rating, we selected the most frequently given rating (even if it was less than 50%). To prioritise the research gaps, we assigned scores based on the rating and the level of consensus, with higher scores given to research gaps with consensus. The top 25 research gaps were then selected in order of their rank.

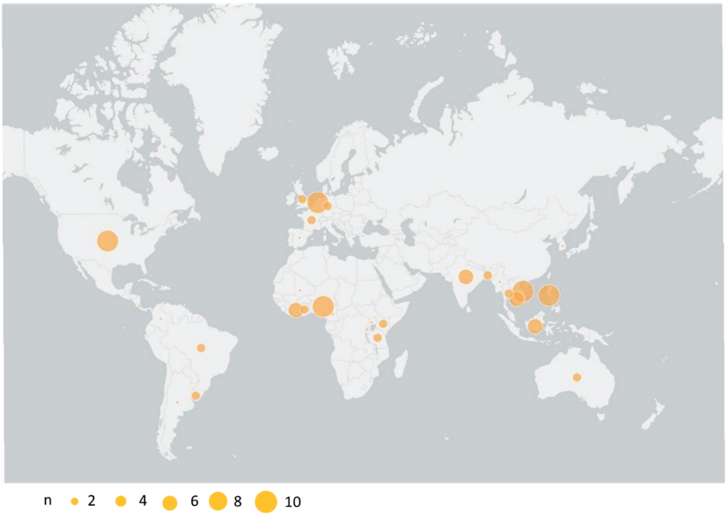


Figure 6.1. Global distribution of rice experts who participated in the horizon scanning activity to identify research gaps for sustainable rice systems by 2050. The size of the bubbles reflects the number of participants from each country, with the bubbles centred over the country rather than the precise location of each participant.

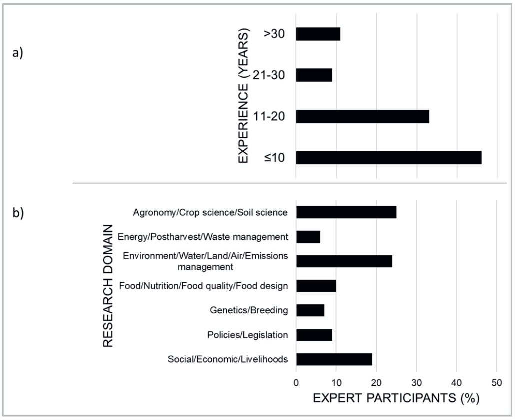


Figure 6.2. Representation of participants in the horizon scanning activity indicating (a) their years of rice research experience and b) research domains. Note that for research domains, participants were allowed to choose multiple domains.

6.4 Results

6.4.1 Drivers

The drivers were listed under present and future times and categorised under Social, Technological, Economic, Environmental and Political. Environmental drivers were identified as the most important category for present and future rice systems, with political drivers as the lowest (Figure 6.3). Other driver categories such as economic, were considered more important now than in the future, whereas technological drivers more important in the future than now. Climate change and technology emerged as important drivers in present and future times (Figures 6.4 and 6.5).

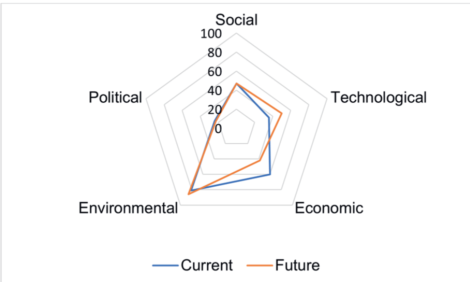


Figure 6.3: Relative importance of driver categories in the present and future times

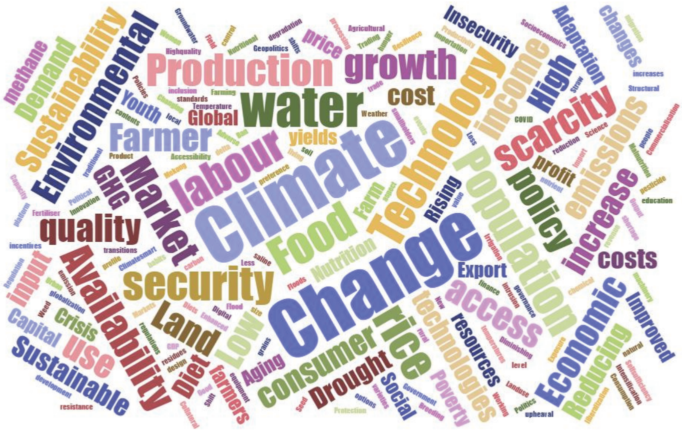


Figure 6.4: Word cloud of drivers important in present times. The size of the word represents the frequency of mention by expert participants.

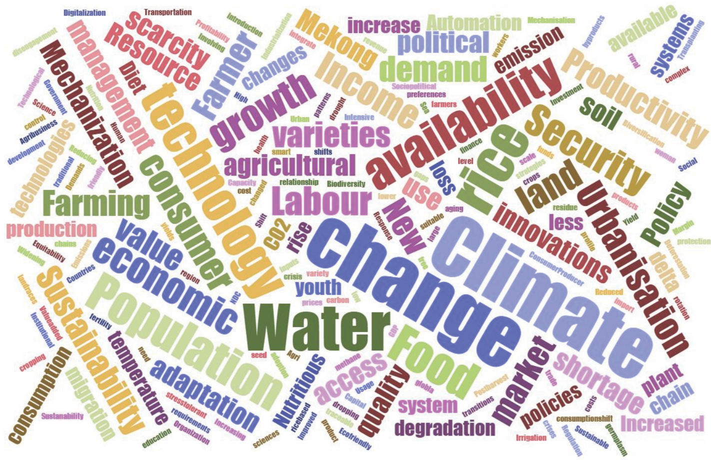


Figure 6.5: Word cloud of drivers important in the future. The size of the word represents the frequency of mention by expert participants.

6.4.2 Projections, Opportunities and Challenges

The analyses of future projections, opportunities and challenges resulted in the identification of seven key issues: climate change, changes in consumer profiles, urbanisation, market and policy shifts, changes in labour demographics, constraints on natural resources and technological advancements. These issues are connected; for example, urbanisation is linked to both changes in labour demographics and consumer preferences (Supplementary material, Table SM6.3).

6.4.3 Research techniques

Proposed research techniques to meet research needs include rice-vegetable systems modelling, digitalisation of value chains, spatial data analytics, stakeholder engagement, lowland development, inter- and transdisciplinary research, remote sensing, water accounting, climate finance and low-emission business models.

Experts also proposed that some research techniques must be applied more to achieve sustainable rice systems. These include digital agriculture, multi-stakeholder engagement, social impact research, satellite imagery, crop insurance, space applications, machine learning, automated crop monitoring, nature-based solutions and systems thinking. In addition, they advocated to shift from one kind of research to another (e.g. crop genetics and plot-level research to farming systems research).

Experts called for 'out-of-the-box' thinking and proposed more inter- and transdisciplinary research. However, some experts wanted basic research that applies critical core expertise. A few other experts called for a long-term vision and funding, while others advocated for rapid technology development and quick R&D cycles. The proposed research techniques are provided in Supplementary material (Tables SM6.3 and SM 6.4).

6.5 The top 25 rice research gaps

54 research gaps from Round 1 were rated by experts and ranked in order of their relevance, novelty and consensus among experts (Table 6.1). The agreement between experts on the ratings of each research gap is shown in Figure 6.6, with a higher consensus for relevance ratings (70%, n=54) compared to novelty ratings (37%, n=54). All relevance ratings with consensus were for 'highly relevant' whereas all but one novelty ratings with consensus were for 'not novel' ratings. The exception is the research gap rank 1 (Table 6.1) related to the trade-offs between mitigating rice greenhouse gas emissions and local food security, which was rated ‘highly relevant’ and 'novel' (see Figure 6.6). The top 25 rice research gaps are discussed below under four themes (Sections 6.5.1 – 6.5.4).

Table 6.1: Research gaps by rank

Rank	Score	Research gap
1	60	Understanding the potential trade-offs between mitigating rice greenhouse-gas emissions and local food security;
2	45	The replacement of manual, in-person Monitoring, Reporting and Verification (MRV) with remote sensing/satellite technology
3	45	Monitoring and assessing the environmental impacts of new rice technology
4	45	Impacts of increasing rice production on Africa's food-crop production and diversity
5	45	Rice varieties that are more efficient in capturing and using environmental resources such as solar energy and aerobic rice that uses less water
6	45	Development of perennial rice varieties; that is, can be harvested season in and season out.
7	45	Maximising increasing CO_2 levels to improve rice-crop ecology and productivity;
8	45	Integration of regenerative and agro-ecosystem approaches in rice systems to optimise productivity and resource-use efficiency
9	45	Expanding dryland and upland rice production
10	45	The governance of surface water use as a collective regional resource and for a balanced supply of rice in a region
11	45	Policy options to mitigate the envisaged rice production loss in some parts of the world, such as Asia
12	40	Socio-economic drivers of rice yield gaps across the world
13	40	Understanding farmers' actual conditions to bridge the profit-loss margin
14	40	Understanding the process of farmers' transformation to sustainable management practices
15	40	Quantifying the local effects on and responses of rice cultivation to abiotic stresses, including climate change
16	40	The effect of increased food insecurity and food prices on farmers' practices of sustainable methods
17	40	The potential socio-economic impact of technological change to small-scale farmers
18	40	Developing accurate climate and water information at local scales
19	40	Developing climate-resilient varieties that can thrive under harsh conditions, e.g. varieties with better stress avoidance traits, highly developed root systems and the ability to grow in saline conditions
20	40	Developing rice varieties with improved grain qualities (such as high milling recovery, head rice, length to width ration)
21	40	Developing methanogenic inhibitors to reduce methane emissions from rice production systems
22	40	Developing innovative agro-ecological fertilisers to improve soil fertility
23	40	Utilising by-products from rice production for other purposes, (e.g. rice straw for biofuels, fertilisers etc.)
24	40	Translating science to practice, (e.g. the application of genetic advancements)
25	40	The policy options needed to boost rice productivity, sustainability and inclusive transformation in lagging regions
26	35	Developing indicators to assess the actual drivers of change in different rice systems, ex. whether due to climate change and/or human population changes.
27	35	Understanding the emerging land grabs and large scale land acquisitions by wealthy farmers/investors due to rising profitability in rice production

28	35	Geospatial analyses of cropland expansion and development of crop-type maps
29	35	Understanding the shifting dynamics of rice consumption due to increasing incomes and urbanisation in different parts of the world
30	35	Developing rice varieties richer in nutritional qualities such as Omega rice, vitamin E rice, high Fe, Zn and low glycaemic content
31	35	Altering the photosynthesis of rice from C3 to C4 pathway
32	35	Developing sustainable local seed systems
33	35	Developing proactive measures to curtail emerging diseases and pests brought by climate change
34	35	Fair sustainable business models and supply chains that results in economic benefits to producers and environmental sustainability
35	35	Planetary health diets: healthy diets with minimal environmental footprint
36	35	Upscaling findings from farm-level (micro-level) to regional/global scale (macro-level)
37	35	Improving the agricultural literacy of rice producers
38	35	Developing indigenous technology to support the rice value chain
39	30	Shared information systems between key players in the rice value chain for increased transparency in MRV
40	30	Converting unproductive areas to rice croplands; due to rising scarcity of arable land
41	25	Developing and utilising genetically modified rice (GMO) and understanding its consequences.
42	25	Impact of urbanisation and industrialisation on availability of arable land for rice production
43	25	Developing floating rice varieties
44	25	New technology development and adaptation of old technology to be suitable and affordable for small-holder farmers
45	20	Understanding the selection and conservation of traditional varieties by farmers.
46	20	The sectoral migration away from farming by youths and by existing farmers
47	20	The impact of changing dynamics in global rice markets such as the attainment of self-sufficiency by current rice importers
48	20	Understanding the interplay and price dynamics between different staple crops (ex. wheat/rice prices) at the global scale
49	20	Growing rice on soil-less media
50	20	Carbon farming solutions towards sustainable systems
51	20	The integration of rice systems with tourism
52	15	Understanding different rice market segments to target rice products to specific markets
53	15	Redirecting rice production from export-oriented production to production for local consumption
54	15	Developing diverse food products from rice grains

	Ratings of relevance			Ratings of novelty		
Rank	LR	MR	HR	NOV	NTM	NTNOV
1	7	28	65	51	13	36
2	14	34	52	43	23	34
3	2	26	72	49	6	45
4	5	38	56	40	30	30
5	0	29	71	37	30	33
6	10	35	55	37	35	28
7	12	32	56	37	33	30
8	5	23	72	48	9	43
9	15	31	54	39	24	37
10	7	36	57	38	29	33
11	5	20	75	47	22	31
12	7	20	74	26	11	63
13	0	36	64	32	9	60
14	0	33	67	41	9	50
15	4	22	73	32	9	60
16	11	32	57	36	13	51
17	2	41	57	32	17	51
18	4	31	64	40	9	51
19	0	19	81	35	11	54
20	2	39	59	22	24	54
21	11	32	58	35	39	26
22	10	19	71	35	15	50
23	10	19	71	37	9	54
24	9	40	51	31	16	53
25	2	26	72	36	11	53
26	7	22	71	43	13	43
27	13	38	50	33	33	35
28	9	41	50	30	28	41
29	5	41	55	32	23	45
30	12	21	67	30	22	48
31	11	26	63	22	33	46
32	5	33	63	37	15	48
33	2	29	69	37	17	46
34	5	35	60	35	17	48
35	19	26	55	28	30	41
36	5	44	51	38	16	47
37	14	31	55	27	27	47
38	29	21	50	31	22	47
39	7	44	49	38	36	26
40	20	34	46	40	31	29
41	26	26	49	26	23	51
42	13	42	44	28	17	55
43	33	33	35	20	30	50
44	16	35	49	29	20	51
45	16	43	41	17	9	74
46	14	37	49	28	23	49
47	15	43	43	30	28	43
48	20	35	45	26	34	40
49	41	24	35	41	39	20
50	5	46	49	37	26	37
51	46	26	28	38	31	31
52	7	47	47	33	18	49
53	31	38	31	20	31	49
54	35	33	33	20	24	56

Figure 6.6: Heat map visualizing the percentage of experts who chose a rating. A green-yellow-red gradient is used, indicating increasing agreement on the rating. The red circle icons represent ratings with majority agreement (≥50%). LR stands for low relevance, MR for moderate relevance, HR for high relevance, NOV for novel, NTM for new to me and NTNOV for not novel.

6.5.1 Theme 1: Sustainability interactions

In achieving sustainable rice systems, tensions probably arise between objectives such as food security and environmental protection (Klapwijk et al. 2014). Balancing these competing objectives and finding trade-offs requires research that considers the interdependencies between different components of the rice-production system and involves stakeholders in the decision-making process.

Climate-change impacts lead to a decline in rice production (Wassmann et al. 2009, Hatfield et al. 2011, Singh et al. 2017). However, it is not certain if climate change also positively affects rice production. Some studies indeed show that climate change could benefit rice production through increased temperatures (Yang et al. 2015, Waha et al. 2020). Therefore, a comprehensive analysis of climate-change impacts is important for innovation in rice production systems. Research on sustainability interactions includes:

1. Understanding the potential trade-offs between mitigating rice greenhouse-gas emissions and local food security;
2. Maximising increasing CO_2 levels to improve rice-crop ecology and productivity;
3. Integration of regenerative and agro-ecosystem approaches in rice systems to optimise productivity and resource-use efficiency;
4. Quantifying the local effects on and responses of rice cultivation to abiotic stresses, including climate change;
5. Developing innovative agro-ecological fertilisers to improve soil fertility; and
6. Utilising by-products from rice production for other purposes (e.g. rice straw for biofuels and fertilisers).

6.5.2 Theme 2: Agricultural development

Agricultural developments and their impacts on social, economic and ecological factors must be thoroughly analysed as they can have far-reaching implications. For example, small-holder farmers grow most of the rice produced and play a substantial role in rice-food security (Pandey et al. 2010) but often receive little monetary benefits from rice production despite rice system expansion. They receive as little as 4% of the consumer price (Alliot and Fechner 2018). This trend counteracts the vision of equitable and sustainable agriculture. Relevant research on agricultural development includes:

7. The replacement of manual, in-person monitoring, reporting and verification with remote sensing and satellite technologies;
8. Monitoring and assessing environmental impacts of new rice technology;
9. Impacts of increasing rice production on Africa’s food-crop production and diversity;
10. Expanding dryland and upland rice production;
11. Socio-economic drivers of rice-yield gaps across the world;
12. Understanding farmers' actual conditions to bridge the profit-loss margin;
13. Understanding the process of farmers' transformation to sustainable management practices;
14. The effect of increased food insecurity and food prices on farmers' practices of sustainable methods;
15. The potential socio-economic impact of technological change on small-scale farmers; and
16. Developing accurate climate and water information at local scales.

6.5.3 Theme 3: Genetics, breeding and physiology

Rice is one of the first crops to have had its complete genome sequenced (Sasaki et al. 2002, Jackson 2016). This advancement marked a milestone in rice research and opened new opportunities for genetic research for other crops (Izawa and Shimamoto 1996, Rezvi et al. 2022). Despite the tremendous success recorded in rice-genetics research (Hossain et al. 2000, Bajaj and Mohanty 2005), much rice genetic and breeding research is still in a developmental stage (Mohd Hanafiah et al. 2020). With the increasing impact of stressors, genetic research needs to be accelerated (Gregorio et al. 2002, Jagadish et al. 2012, Hasanuzzaman et al. 2018). The research gaps list the directions for rice genetic research on developing:

17. Rice varieties that are more efficient in capturing and using environmental resources such as solar energy and aerobic rice that uses less water;
18. Perennial (i.e. can be harvested season in and season out) rice varieties;

19. Climate-resilient varieties that can thrive under harsh conditions (e.g. varieties with better stress avoidance traits, highly developed root systems and the ability to grow in saline conditions);
20. Varieties with improved grain qualities (such as high milling recovery, head rice, length-to-width ration); and
21. Methanogenic inhibitors to reduce methane emissions from rice production systems.

6.5.4 Theme 4: Governance and policies

Policies and equitable governance support agriculture to achieve diverse objectives offering the opportunity to minimise losses and maximise synergies across scales. For example, persistent transboundary policy-practice mismatches in the international Mekong Delta's management have led to lower agricultural production and poor water management (Thu and Wehn 2016, Sithirith 2021, Tran and Tortajada 2022). Effective policies must integrate knowledge from multiple fields and scales (Sterner et al. 2019). The research gaps under this theme relate to the science-policy-practice gap and the implementation of effective policies to resolve sustainability issues. Research on governance and policies include:

22. The governance of surface water use as a collective regional resource and for a balanced supply of rice in a region;
23. The policy options to mitigate the envisaged rice production loss in some parts of the world, such as Asia;
24. Translating science to practice (e.g. the application and adoption of genetic advancements); and
25. The policy options needed to boost rice productivity, sustainability and inclusive transformation in lagging regions.

6.6 Conclusions

We conducted a horizon scanning activity to identify research gaps that need to be prioritised for sustainable rice systems by 2050. The horizon scanning involved a global panel of rice experts in a two-round Delphi-technique. The activity resulted in drivers, projections, opportunities, challenges, research gaps and techniques.

Most research gaps were considered 'highly relevant' and 'not novel'. To tackle these persistent issues, further research is needed that builds upon existing findings and helps end-users utilise research results. Our study aligns with Dalton's notion of horizon scanning (Dalton 2002), which identifies both novel and persistent research gaps. A sustainability transition is often referred to as a shift towards a sustainable state in response to the persistent issues facing modern societies (Grin et al. 2010). Hence, it is important to address the persistent issues identified in our study to achieve sustainable rice systems.

The top 25 rice-research gaps have different degrees of agreement among the global panel of experts and this shows a diverging consensus on several issues. Research gaps that are future-oriented and at the margins of our current thinking are rarely a product of consensus (Kramer et al. 2017). Also, little conformity in knowledge is expected when experts come from diverse research and cultural backgrounds. However, consensus serves as evidence to support the ranking of the horizon-scan output (Hines et al. 2019).

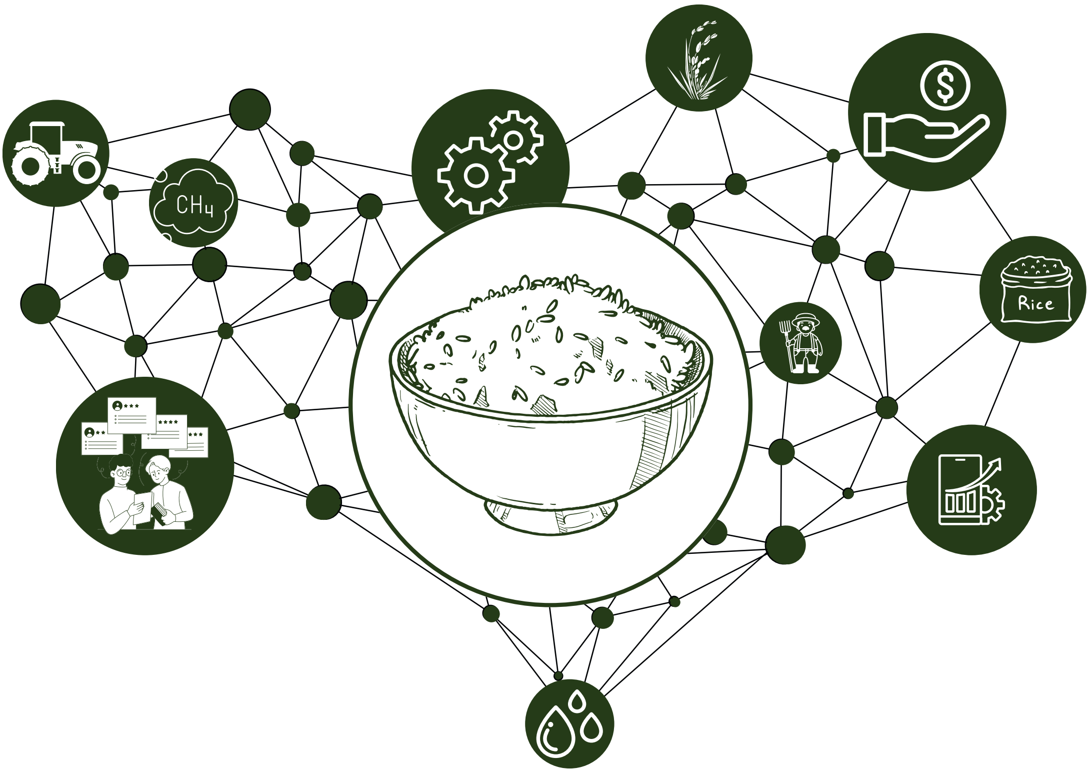
Horizon scanning is a crucial first step in the foresight process, as it identifies emerging trends and potential challenges (National Academies of Sciences 2020, Cuhls 2020) and thus should be conducted regularly to keep track of changes over time (van Rij 2010). The success of horizon scanning can be seen in examples such as the yearly scans on global conservation issues (Sutherland et al. 2019). In this context, our study could be considered the first phase in a long-term foresight process, which can help track the progress of rice research over time.

Our study involved experts from the broad domain of rice research, but further research can take the same approach to different groups of experts or stakeholders. Results could be compared to see where results align or differ between stakeholder groups, increasing the results' applicability to policy and practice. Further research could, for example, engage farmers who apply research results (MacMillan and Benton 2014); government funding agencies who are the key investors in AgR&D (Alston et al. 2012); and businesses in the agriculture or private sector that increasingly invest in research (Pardey et al. 2016).

Our study also contributes to the research priority setting by being conducted worldwide. Research priority setting for rice is often regional or national (e.g. Evenson et al. 1996, Barker and Herdt 2019) or focused on sub-domains of rice research (Hossain et al. 2000, Willocquet et al. 2004). A few worldwide studies have been conducted, but these relied on bibliometric analysis to prioritise research (Pandey et al. 2010, Bin Rahman and Zhang 2022). But our study capitalises on knowledge from a global panel of rice experts, hence, the research gaps are relevant to global food security and sustainability. Furthermore, by presenting the top 25 rice research gaps, experts can focus on the areas of need and collaborate, leading to more effective and impactful research outcomes. In addition, our study acts as a bridge between researchers, funding agencies, policymakers and end users by highlighting a set of research to be prioritised.

Chapter 7

Synthesis



7.1 Introduction

Agricultural and food systems must increase production while preserving natural capital to ensure food security and sustainability. The grand challenge of sustainable agricultural production is also stressed in UNFCCC's Paris Agreement: 'food production should not be compromised while working towards climate-change adaptation, mitigation of greenhouse gas (GHG) emissions and resilience.' This challenge presents tensions between its objectives due to these systems' complex nested and dynamic nature, their inherent heterogeneity and multiple interacting dimensions and scales. A comprehensive integrative analysis of these complexities, interactions and interdependencies is necessary to attain sustainable systems. In my thesis, I contribute to this need for integration by focusing on rice sustainability through a systems-thinking approach. Such an approach helps to comprehensively understand the interactions and dynamics within rice systems and identify strategic interventions to enhance future sustainability across various dimensions.

My thesis addressed the following research questions (RQs):

RQ1: What national-level variations in key characteristics have shaped the historical and present sustainability of rice systems?

RQ2: What is the current structure, functioning and related dynamic behaviour of rice systems?

RQ3: What are the implications of future social, economic, environmental and institutional changes on the sustainability of rice systems?

RQ4: What pathways and strategies need to be established to ensure the sustainable development of rice systems?

These RQs, each focused on a rice sub-system, were addressed in Chapters 2 to 6. In this Synthesis chapter, I summarise the main results related to each RQ (Sections 7.2 - 7.5) and condense these research results into a system map in the context of the overall thesis objective (Section 7.6). The system map shows the factors studied and the relationships between these factors. The system map summarises the key research findings that contribute to our understanding of (un)sustainability in rice systems. In addition, in this Synthesis Chapter, I reflect on the methods used and show how integrating the methods improved the research on rice systems (Section 7.6).

7.2 Variations in the resilience of rice systems to rice price spikes

7.2.1 Main findings and reflection

In Chapter 2, I analysed the resilience of rice systems using national-level data from 71 countries (RQ1). Five archetypes were identified: 'Laggards'; 'Emergers'; 'Grain and Water'; 'Midfielders'; and the 'Thrivers'. These archetypes differ in their resilience, which is their capacity to ensure rice-food security during international rice-price spikes **(*resilience* → *food and nutrition security*)**. The combinations of multiple factors can make a country more resilient. When a country has an unmet rice demand and relies on rice imports, it is likely to be affected by global rice-price spikes **(reliance on international markets → *resilience*)**. But such a country can buffer the impacts of high prices in international markets by having economic resources to participate and adapt in times of rice price spikes (***socio-economic developments* → *resilience*)**.

The archetype 'Laggards' has a low production capacity, low GDP per capita and strong import dependency. The 'Emergers' have low but increasing production capacity and economic abilities. 'Grain and Water' has high production capacities due to significant irrigation infrastructure (**farm technology and infrastructure → *rice yield* → *rice production*)**. 'Midfielders' also have a high production capacity and consumption. Finally, the 'Thrivers' have high production capacities, high GDP and low import dependency. The 'Laggards' and 'Emergers' archetypes are less resilient due to their higher import dependencies than the other archetypes.

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From my results and as also mentioned in other studies (e.g. Puma et al. 2015, Bren d'Amour et al. 2016), countries with similar resilience are clustered together, often in the same regions. Thus, international food crises are likely to affect entire regions rather than just single countries. The consequences of interactions depend on their reliance on international markets, as ties with foreign exporters reduce a country's resilience. Shifting reliance from cross-continental exporters to regional rice producers increases a country's resilience, as observed in West Africa (Aker et al. 2012, Mendez-del-Villar and Lançon 2015, Tondel et al. 2020, Ibrahim et al. 2021) (***regional collaboration → reliance on international markets → resilience).***

Although I derived distinct archetypes, the archetypes are not ranked in their resilience. The analysis particularly captured the variation between archetypes. Each archetype's vulnerabilities result from a combination of factors (i.e. combinations of different factors i cause countries to be more or less resilient). By emphasising the specific characteristics of each archetype, a better understanding of the key factors that have shaped the impact of food crises and the countries' capacities to maintain rice food security, is enhanced. Focusing on the challenges unique to each archetype enhances the resilience and sustainability of national and global rice systems.

7.2.2 Methodological reflection

In Chapter 2, I used a 2-step procedure to derive archetypes of resilience to rice price spikes. First, a cluster analysis using 2016-2019 data was performed to capture the short-term resilience in countries resulting from their production capacity, socio-economic developments and market-based factors. Next, a time-series analysis was performed on the output from the cluster analysis using long-term data from 1961-2019 to characterise the archetypes. By doing so, I incorporate short- and long-term resilience in the archetype analysis. The development of resilience concepts has evolved to emphasise the time dimension (Constas et al. 2021). Resilience highlights the long-term capacity of countries to recover from shocks (Béné et al. 2016).

Resilience is an integrative concept (Tendall et al. 2015, Béné et al. 2016) that incorporates several explanatory factors into an assessment (Constas et al. 2021). The datasets used for the analysis included production and market-based data (e.g. suitable area for rice cultivation, area equipped for irrigation, yield, per capita consumption, import dependency ratio, GDP per capita and production per capita). The dataset was limited to quantitative data and excluded qualitative or non-numerical data. As such, the factors that could be included are restricted to factors with numeric values. This risks that some factors that could contribute to the resilience assessment but are not quantitative, remain excluded. Additionally, for a worldwide analysis to be possible, only factors related to rice and available in public databases for many countries were included. The study's relevance to rice price spikes in particular and the study's reproducibility improved this way.

7.3 Unsustainable patterns in current rice systems

7.3.1 Main findings

In Chapters 3 and 4, I and my collaborators focused on Nigeria's rice-system to understand the current structure, functioning and related dynamic behaviour of rice systems (RQ2). Rice production has increased in Nigeria, but historically this is mainly from rice area expansion and less from yield improvements (c.f. Figure 4.1, Chapter 4). Low yields harm the natural resource base and this perpetuates a negative feedback loop that further limits rice yields.

The self-sufficiency goal, implemented through import restriction policies and agricultural investments by the Nigerian government, has widened the rice demand-supply gap ***(import restriction policies → rice demand → rice demand-supply gap)***. In response, more farmers take up rice farming, expanding the rice area towards increasing rice production to reduce the demand-supply gap (***rice demand-supply gap → rice land → rice production → rice demand-supply gap)***. Rice-area expansion is a 'low-hanging fruit' but only a temporary solution, especially in countries with abundant land resources. Rice-area expansion has long-term consequences, such as soil degradation, which lowers rice yields and agricultural productivity (***rice land → soil degradation and natural resource loss → rice yield)***. This pattern of 'low yields, more area expansion' has persisted. Yields can be increased sustainably through several ways, including mechanisation, irrigation infrastructure and other improved farm technologies mentioned by stakeholders in Chapter 4 (***farm technology and infrastructure → yield***). In this study, the issue of mechanisation was highlighted as a deterrent or enabler of sustainable rice production, as also mentioned in other studies, especially for African farms that are the least mechanised globally (Sims et al. 2016, Daum and Birner 2020). Further contextual studies need to assess the outcomes associated with mechanisation.

Low rice production also implies that the demand-supply gap created by the import restriction widens further. Without imported rice alternatives, local rice prices increase

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and this causes food insecurity (***import restriction policies → rice demand → rice demand-supply gap → rice price).*** A solution for the government would be to bridge the demand-supply gap by removing import-restriction policies entirely or partially. Any of these solutions has implications for food security. Lowering the import-restriction policies reduces local rice demand and production but considers the time needed for local rice production to increase to meet rice demand. Removing the import restriction policies leads to a stagnant local rice system where imported rice floods the market and local rice demand drops. The system's complexity makes achieving sustainability a wicked problem, a problem with no clear-cut solutions, as many different stakeholders' norms and values are involved. System archetypes contain unsustainable patterns and embedded strategies (Kim 1995) that likely advance sustainability in Nigeria's rice system.

7.3.2 Methodological reflection

Chapters 3 and 4 aimed to understand and analyse the structure and behaviour of Nigeria's rice system and to propose effective solutions to address the problems embedded in the system. I considered that understanding this system is best held by those living and working in the system and thus selected a method that included stakeholder engagement. Stakeholders were selected using a quota system, the Prospex-CQI, which fosters a fair stakeholder selection and inclusion (Gramberger et al. 2015). Our participating stakeholders included farmers, agri-business owners, rice trade unions, government officials working in relevant agencies, researchers, extension workers. A diverse set of stakeholders contribute various perspectives on the system which are aggregated into a fuzzy cognitive map (FCM).

I chose fuzzy cognitive mapping, which can be developed from a participatory stakeholder process. Fuzzy cognitive mapping is suitable for gaining insights into a specific context at local scale. Stakeholders can participate effectively in research using fuzzy cognitive mapping. Chapter 3 describes a structured method to elicit knowledge of the system from stakeholders through fuzzy cognitive mapping. I considered the contextual limitations in involving stakeholders so I ensured that I used a common form of communication in Nigeria – telephone communication. This way, the stakeholders did not require special software or hardware or come to a meeting place to participate in the research. Stakeholders did not need specific qualities or skills to create a FCM except their knowledge of the system which was elicited through semi-structured interviews in a telephone conversation.

FCMs also enabled the inclusion of quantifiable and difficult-to-quantify aspects of such a complex system and its different domains (Kafetzis et al. 2010). Stakeholders use strong, medium and weak linguistic values, which the co-authors and I needed to translate into numerical values. Realising the subjective character of the translation, we analysed the effect of various sets of numerical translations of strong/medium/weak for the FCM dynamic output. Although absolute stabilising factors differ, the outputs were very similar. In an aggregate map, the choice of weights has much less impact on the overall output as differences in assigned values average out.

The participatory process did not only produce qualitative, non-numeric data. The stakeholders also contributed quantitative knowledge of the rice system by providing weights for the connections. Stakeholders provided weights for the fuzzy cognitive map. These weights also served as inputs for the quantitative simulation that determined the system's behaviour. Changing the system's drivers resulted in different system states which can represent different scenarios. Typically, causal loop diagrams are used to identify system archetypes (Kim and Anderson 1998, Wolstenholme 2003), but I innovatively use FCMs in my study as the fuzzy cognitive map's feedback loops are the building blocks of the system archetypes.

Three generic system archetypes ('limits to growth', 'fixes that fail' and 'drifting goals') were identified from the fuzzy cognitive map. Understanding a complex system enables projections into the system's future (Ren et al. 2018). The factors of a system are linear, but the relations with other factors often result in non-linear behaviour. This can be used to project how the system will likely behave under the different influences of the drivers. Fuzzy cognitive mapping proved a useful foresight tool by generating 'what-if' scenarios using the different drivers in Nigeria's rice system.

7.4 Quantifying GHG emissions by location, season and management practices

7.4.1 Main findings

In Chapter 5, I aimed to provide scenarios of future land-use change driven by socio-economic and environmental development and quantify greenhouse gas emissions from spatial patterns of land-use change in Vietnam (RQ3). In essence, to better understand the potential implications of future changes on the sustainability of rice systems from a GHG-emissions perspective. GHG emissions are an externality from agricultural production that is not often internalised and accounted for (Bithas, 2011; van den Bergh, 2010) but contribute significantly to climate change **(*GHG emissions → climate change).***

Chapter 5 uses location-specific and season-specific emission intensities to calculate rice land GHG emissions in Vietnam. The results show that rice land emits different fluxes of GHG (methane) under different management practices ***(rice land* → GHG *emissions*)**. Expanding built-up areas, grasslands, croplands and orchards contribute to GHG emissions through land-use and land-cover change (***soil degradation and natural resource loss* → GHG *emissions***).

Disaggregating the rice-GHG emissions by locations, seasons and management practices was a valuable evaluation of the magnitude and spatial extent of GHG emissions from rice production. In the most sustainable scenario, the total GHG emissions were negative, showing that land can become a sink rather than a source of GHG emissions due to mitigation measures and resource management ***(sustainable rice practices* → GHG emissions)**.

The scenario narratives derived from which the land use demands were calculated reflect the challenge of ensuring climate change adaptation and mitigation while increasing the productivity and production of rice. This research subject on GHG emissions, food security and sustainability was identified in Chapter 6 Horizon scanning activity. Therefore this chapter already contributes to the research gap specified in Chapter 6 as highly relevant and novel: 'Understanding the potential trade-offs between mitigating rice greenhouse-gas emissions and local food security'.

7.4.2 Methodological reflection

This research aimed to derive scenarios of future land use change driven by socio-economic and environmental development and to quantify greenhouse gas emissions from spatial patterns of land use change in Vietnam. The results focus on rice cultivation but link to other land uses, indicating the spatial interdependencies of land use classes.

The Conversion of Land-use and its Effects (iCLUE) model was used to spatially allocate land whereas the Source-selective and Emission-adjusted GHG CalculaTOR for cropland (SECTOR) to estimate GHG-emission intensities under different land uses and management conditions. The GHG-emission intensities for each land use were calculated from Vietnam national inventory report for varied by different rice-management practices. The rice-cultivation methane-emission intensities were calculated using location-specific and season-specific emission factors (Vo et al. 2020).

Different models have been applied to estimate CH_4 emissions and assess mitigation potentials for rice cultivation. Some examples are DAYCENT (Beach et al. 2015), DNDC (Beach et al. 2015, Hwang et al. 2021), AFOLU-B (Hoa et al. 2014, Hasegawa and Matsuoka 2015, Jilani et al. 2015, Pradhan et al. 2019), SWAT (Gassman et al. 2022) and ECOSSE (Begum et al. 2019, Kuhnert et al. 2020). These models are complex and process-based and require huge amounts of high-resolution data and programming expertise (Del Grosso et al. 2012, Hwang et al. 2021). Sometimes these models focus on specific aspects (e.g. nitrogen: DNDC and soil carbon: ECOSSE). Such models that focus on a single component of a system are inadequate in capturing complex dynamics of rice systems. Models, which require less data and are more empirical and generally easier to implement (Olander et al. 2013), are better suited for country-level estimates (Wang et al. 2018).

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Our study presented a parsimonious modelling approach to estimate land-based GHG emissions using the iCLUE model and the SECTOR tool. The iCLUE model facilitates scenario analysis and enables various impact measurements (Verweij et al. 2018). The SECTOR tool is quite flexible as it allows for the emission factors to be updated and other input data to be determined (Nelson et al. 2022). A rising number of studies have applied the SECTOR tool not only for emissions quantification but also to test the influence of, for example, fertilisers on yields (Mboyerwa et al. 2022). Our study advances the use of GHG calculation tools by linking its output with a spatially explicit model.

This chapter is the only chapter to apply such spatially explicit method, adding value to the entire thesis by demonstrating the importance of spatially explicit information in achieving sustainability in rice systems. While many other methods are likewise useful to identify problems and propose strategies in the system, spatially explicit methods, additionally, guide the selection of locations and seasonal timing indicating where and when GHGs should most effectively be reduced.

Although the end result is spatially explicit and quantitative, the study began as a story-and-simulation (Alcamo 2001, 2008). I and the collaborators along with experts who were consulted derived scenario narratives (story) and converted these narratives to quantitative land use demands which became iCLUE model inputs. The results from the model calculations (simulation) complement the scenario narratives. The scenarios were downscaled from the global shared socio-economic pathways (SSPs) to Vietnam national scale, therefore making the global SSPs more locally relevant. The participation of experts in deriving these scenarios ensured that the scenario narratives and the land-use demands for each scenario were contextually nuanced, adding depth and credibility to the scenarios, thus enriching the entire scenario-building process.

Although the SECTOR tool outputs were incorporated as part of the iCLUE model input, they were not directly linked. Future studies should focus on advancing the iCLUE model and the SECTOR tool, potentially establishing a dynamic linkage between them. The iCLUE model and the SECTOR tool address the need for cost-effective, less complex, feasible and user-friendly models for national inventory reporting (Olander et al. 2013). Further applications of these modelling tools hold promise for advancing our understanding of the relationship between land management and GHG emissions, facilitating the development of effective strategies for mitigating emissions and promoting sustainable land use practices.

7.5 Future research for sustainability in rice systems

7.5.1 Main findings

Chapter 6 conducted a horizon scanning to identify research that needs to be prioritised (RQ4). The top 25 research gaps to be prioritised were grouped into four themes; 'Sustainability Interactions'; 'Agricultural Development'; 'Genetics, Breeding and Crop Physiology'; and 'Governance and Policies' (***research for sustainability → sustainable rice practices)***. Research pathways to sustainability mentioned by the experts include building on existing findings, using innovative approaches and helping end-users utilise research results to solve persistent issues. Experts called for 'out-of-the-box' thinking and proposed more inter- and transdisciplinary research. Some experts want more funding for basic research that applies critical core expertise, such as crop genetics. A few other experts called for a long-term vision and funding, while others advocated for rapid technology development and quick R&D cycles, which emphasised short-term implementation and immediate results. The horizon scanning highlighted heterogenous research needs that lead to more effective and impactful outcomes. Most research requires strong inter- and transdisciplinary collaboration. These results are also relevant for funding agencies and policymakers ***(sustainability policies and investments → research for sustainability)***.

Most of the research gaps were classified by experts as highly relevant but not entirely novel. Overall, my study emphasised that many challenges have long persisted for rice research and will become even more important. Experts contributed to developing sustainable rice systems by prioritising and addressing the research gaps.

Overall, achieving sustainable rice systems requires the current, persistent research needs to be met while pursuing emerging challenges. That is, new research should build on past research and development endeavours, following Newton's famous expression of building on the ideas of others (Newton 1675[1]).

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[1] https://en.wikipedia.org/wiki/Standing_on_the_shoulders_of_giants

7.5.2 Methodological reflection

My research in Chapter 6 aimed to identify research gaps that should be prioritised to achieve sustainable rice systems by 2050 using horizon scanning. The focus was on international research gaps but as my research in the other chapters focused on local, regional and national aspects, research gaps could be specified at any scale. Experts, therefore, contributed to some regional and country-specific research gaps.

Most past studies have focused on sub-domains of rice research (Hossain et al. 2000, Willocquet et al. 2004) or on regional or national aspects (e.g. Evenson et al. 1996, Barker and Herdt 2019) to identify rice research gaps. Many worldwide studies relied on bibliometric analyses to prioritise research (Pandey et al. 2010, Bin Rahman and Zhang 2022). Bibliometric analysis is typically retrospective, looking into past publications and is limited to what is already known or provides a short-term forecast (Wallin 2005, Donthu et al. 2021).

To address the need to incorporate unique, relevant and novel insights, I required a method that enables long-term foresight. Horizon-scanning activity implemented through a two-round Delphi technique proved to be appropriate. The horizon scanning allowed international rice experts to contribute their knowledge on emerging developments beyond what is available in published literature. First, experts provided research gaps as open-ended answers. In the second round, experts provide ratings in relevance and novelty to a list of 54 research gaps condensed from the 1st round.

Ideally, the research would have benefited from more rounds but to avoid participant fatigue, we maximised the two rounds with experts by settling on a 50% level of consensus after the 2nd round. If there was no consensus on any rating, we selected the most frequently given rating (even if it was less than 50%). To prioritise the research gaps, we assigned scores based on the rating and the level of consensus, with higher scores given to research gaps with consensus. The top 25 research gaps were then selected based on rank.

Consensus serves as evidence to support the ranking of the horizon-scan output (Hines et al. 2019). However, research gaps that are future-oriented and at the margins of our current thinking are rarely a product of consensus (Kramer et al. 2017). Also, little conformity in knowledge is expected when experts come from diverse research and cultural backgrounds. However, consensus is an important criterion for a Delphi technique horizon scanning activity, as such a minimum of three rounds is optimal to ensure the output is a product of group opinion (Trevelyan and Robinson 2015).

Horizon scanning is a crucial first step in the foresight process, as it identifies emerging trends and potential challenges (National Academies of Sciences 2020, Cuhls 2020), as such I recommend the horizon scanning we performed as the first phase in a longer-term foresight process. The progress of rice research over time should be carefully and independently monitored and, if necessary, adapted to new future trends and needs. An example of an ongoing foresight process is the horizon scans on conservation issues carried out yearly since 2009 (Sutherland et al. 2019).

Our study involved experts from the broad domain of rice research, but further research can take the same approach to different groups of experts or stakeholders. Results could be compared to see where results align or differ between stakeholder groups, increasing the results' applicability to policy and practice.

7.6 Integration

7.6.1 Creating a system map to assess pathways to sustainability

After working on rice systems across spatial, temporal and disciplinary dimensions, I have gathered knowledge and insight into the structures and behaviours of rice systems. This knowledge is reported in the research chapters as the main findings and summarised in the Synthesis chapter (Sections 7.2 – 7.5). I now condense these findings into a system map, which is a visual summary of the collective rice system (Figure 7.1). The system map makes the interacting factors explicit and explain how they contribute to (un)sustainability. The map is not an absolute description of the rice system but is my description of the rice sub-systems studied represented as a collective rice system. I derive the factors and their relationships from the key findings of my thesis. Therefore, the system map is not unfounded but rather links to the research results.

The system map lets me articulate and visualise my understanding of rice systems. Likely a different system-map configuration results from another person's attempt to synthesise the findings from the thesis research chapters. Many other relationships between factors are possible in the system map from the wider literature. However, I include only relationships supported by my research results, which I consider key factors of rice systems.

Practically, I drew the system map following a 'story-to-structure' mode, often used to identify recurring patterns in complex systems by converting narratives (story) to factors and their relationships (system structure) (Kim and Anderson 1998). As such, during the synthesis of research results in Sections 7.2 – 7.5, I provided relationships between factors in brackets that directly translate the main research findings to the system map. Mapping the system and its relationships (Figure 7.1) revealed patterns in the rice system structure and drew attention to multiple pathways to sustainable rice systems.

The map consists of twenty factors and forty connections. There are three drivers (i.e., 'Import restriction policies', 'socio-economic developments' and 'sustainability policies and investments'), whereas the other factors are transmitter factors with both incoming and outgoing arrows. Resilience and rice production have the most connections. The system map contains three reinforcing feedback loops (R1, R2 and R3) and two balancing loops (B1 and B2). I matched these with generic system archetypes and identified that the Loops R1, R2 and R3 are characteristic of a 'limits to growth' system archetype (Kim and Lannon 1997). Loops B1 and B2 are characteristic of a 'balancing loops with delay' archetype (Wardman, 1994). The complexity and dynamics of these feedback loops give rise to emergent phenomena, which explain the more complex systemic outcomes beyond the linear interactions of individual factors. The feedback loops between interacting factors cause the recurring problems of unsustainability in rice systems. So, solutions to the patterns of unsustainability observed in rice systems can probably be solved by revealing and targeting the problem points in the system (Senge 1990, Kim and Lannon 1997). Therefore, I look into these feedback loops and their embedded solutions.

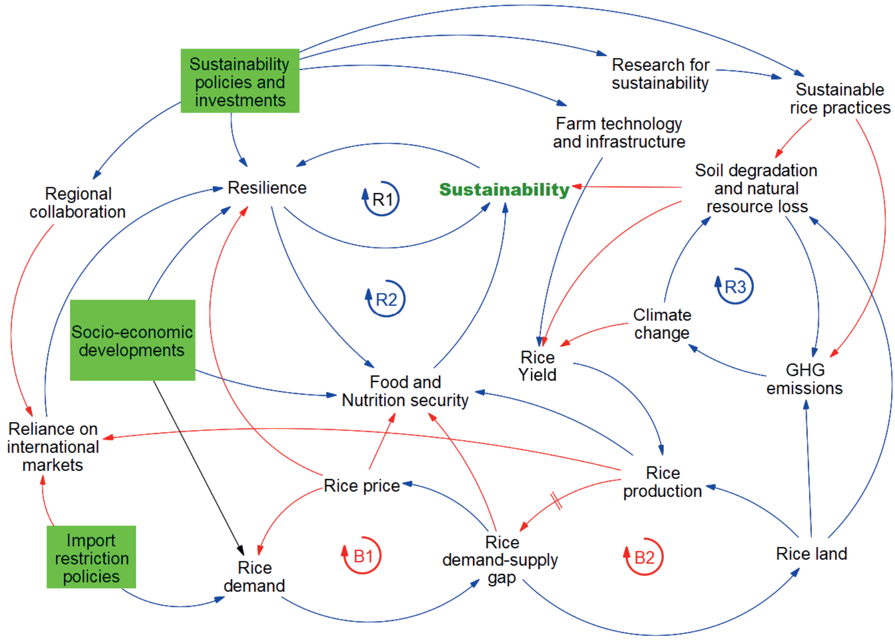

Figure 7.1 System Map synthesising the findings from Chapters 2 - 6. Unless specified otherwise, this map captures various factors from a national perspective. Red arrows represent inverse or negative relationships and blue arrows define direct or positive relationships. The relationship between socio-economic developments and rice demand is in black to differentiate from other relationships because socio-economic developments can have either a positive or negative influence depending on the country. The drivers are in green boxes, with outgoing arrows and no incoming arrows from the system. R1, R2 and R3 are positive feedback loops whereas B1 and B2 are negative balancing loops that constrain dynamics in the system. Loop B2 has a delay mark between rice production and the rice demand-supply gap. Sustainability is highlighted in green text as the central factor.

Resilience, food security and sustainability are linked through loops R1 and R2 (Figure 7.1). Resilience refers to the capacity of a food system to withstand shock while maintaining desired outcomes such as food security (Hoddinott 2014, Tendall et al. 2015, Schipanski et al. 2016).

In Chapter 2, the resilience of rice systems was identified from its current state and capacity over time to maintain production and productivity despite global rice price spikes. These properties link resilience to sustainability as both concepts consider the present and long-term outcomes (WCED 1987). The feedback loops R1 and R2 emphasise the interdependencies between resilience and food security and that sustainability is strengthened by the resilience of rice systems and the delivery of desired outcomes - food security. This is well established from other resilience studies on food systems (Tendall et al. 2015, Béné et al. 2016, Seekell et al. 2017, Constas et al. 2021).

In loop R3, soil degradation and other natural resource losses, such as forest and water loss, contribute to declining sustainability. This linkage draws attention to the environmental feedback from land use that affects system sustainability. The feedback loops R1, R2 and R3 represent a 'Limits to success' system archetype where a factor limits a reinforcing accelerated growth loop. The prescriptive action identifies the links between the growth process and the limiting factor and determines ways to manage the two (Kim 1995). In this case, agricultural production provides many benefits to humans but soil degradation and depletion of natural resources result from agricultural production. The anthropogenic exploitation of natural resources for agricultural production must be balanced to maintain and sustain natural resources for the future. As long as rice is produced in unsustainable ways, unintended side effects will follow, undermining future rice production. This situation connects to the broader subject of maintaining planetary boundaries and environmental limits within food systems (Rockström et al. 2009, Firbank et al. 2018, Fischer 2018, Springmann et al. 2018).

The grand challenge of sustainable agriculture is evident in different rice systems. For example, Vietnam (Chapter 5) represents rice systems with high yields, significant rice exports, playing a major role in global rice markets. However, Vietnam's success has come at an environmental cost. The heavy reliance on chemical fertilisers and pesticides during the Green Revolution initially led to increased yields and economic gains. However, the failure to mitigate the ecological impacts of these practices has resulted in environmental degradation, soil pollution, water contamination, biodiversity loss and likely also impacts on human health. These externalities ultimately undermine the contribution of rice production to food security.

Nigeria's emerging rice system (Chapters 3 and 4) is driven by the desire to reduce import dependency but also faces environmental problems, specifically soil degradation caused by low yields and uncontrolled expansion of rice-cultivation areas. Environmental degradation is a common factor in both Vietnamese and Nigerian systems. By focusing solely on increasing rice production without considering the broader ecological context and long-term sustainability, both countries have experienced negative long-term outcomes. In either system, ignoring the environment and better integrated resource management results in unintended consequences. Rice production is not synonymous with environmental degradation and it should not be. The negative consequences of unsustainable rice practices have far-reaching environmental effects locally and contribute to climate change and global warming. Hence, the Nigerian and Vietnamese case studies indicate the importance of sustainable rice production at local and global scales.

The balancing loops in the system map (Figure 7.1) – B1 and B2 relate to rice demand and supply dichotomies. If the demand for rice increases in any country beyond its supply, rice prices likely increase due to the demand-supply gap. Loops B1 and B2 are coupled loops that represent this demand-supply interaction, especially in countries with high per-capita rice consumption where the demand for rice is inelastic and is considered a necessity commodity with no close substitutes. These interactions lead to high prices which when accompanied by delays in increasing rice supply to meet rice demand lead to food and nutrition insecurity (Loops B1 and B2, Figure 7.1). This system structure was observed in Nigeria's rice system, where import restriction policies increased local rice demand. But, because local rice production had not increased sufficiently to meet this new demand, rice market prices increased, leading to food insecurity, especially for vulnerable groups. This finding was obtained through co-production with stakeholders and is contextually relevant to Nigeria's rice system. Governments fail to recognise the time it takes for rice supply to rise to meet demand when import restriction policies are implemented, leading to food insecurity.

Consumer behaviour also has the potential to reduce rice demand when supply does not meet up with demand. Socio-economic developments dictate rice demand levels, with Africa showing higher rice demand with higher income, whereas Asia exhibits lower rice demand with higher incomes (Nigatu et al. 2017, Bin Rahman and Zhang 2022) ***(socio-economic developments** ---(increase or decrease)* **→ *rice demand).***

Socio-economic development also drives rice availability in Africa by enabling countries to participate in international markets (De Vos et al. 2023). On the other hand participating in international rice markets (especially as a net importer) predisposes countries to global shock events such as price spikes and conflicts (Bren d'Amour et al. 2016, Cottrell et al. 2019, Kuemmerle and Baumann 2021, Hellegers 2022).

Chapter 2 of my thesis investigated resilience to price spikes in rice and I found that less resilient countries were concentrated in Africa and Asia. These are the top regions where most rice produced globally is consumed (Elert, 2014). The concentration of low resilience in these regions indicates a skewed global food system, potentially with consequences for regional and international food security.

In addition to national strategies, regional collaborations will contribute to reduce resilience to international shocks. Countries can collectively address common challenges, harmonise trade policies and ensure a stable rice supply. Such collaboration also facilitates sustainability through knowledge exchange on sustainable practices for rice cultivation; for example, Sustainable Rice Practices (Zeigler and Dobermann 2019).

Regional initiatives such as the Coalition for African Rice Development (CARD) have led to yield improvements (Arouna et al. 2021). Another example is the Asia-RICE initiative which applies satellite remote sensing technologies for rice mapping and has increased regional rice production (Sobue et al. 2022).

The claims and debates on promoting more localised or more globalised food systems has persisted (Clapp 2017, Enthoven and Van den Broeck 2021, Wood et al. 2023). It is not definitive if self-sufficiency (localised or regionalised rice systems) or greater coordination of rice systems globally is better for sustainability. For this reason, I have differentiated between 'import restriction policies' and 'sustainability policies and investments' in the system map (Figure 7.1). Import restriction policies as seen in the Nigeria's rice agri-food system does not always result in food security and sustainability. On the other hand, high import dependency ratios lead to low resilience and low sustainability . On the other hand, for a net exporter of rice Vietnam, unsustainability results from GHG emissions from rice cultivation.

7.6.2 The role of archetype analysis

In the Introduction (Chapter 1), archetype analysis as a technique was introduced under which I chose two methods to implement different archetype analyses. In Chapter 2, we carried out 'archetypes by typologies' using cluster analysis whereas in Chapter 4, 'archetypes as building blocks' was conducted.

In Chapter 2, I analysed 71 countries in a worldwide analysis, reducing the data heterogeneity into five archetypes (worldwide – national downscaling). In Chapter 4, I matched Nigeria's case-specific rice system structure (through its feedback loops and system behaviour) with generic system archetypes which have been observed worldwide and published in systems thinking literature (Senge 1990, Kim 1995, Kim and Lannon 1997), typifying a national-worldwide upscaling I used these system archetypes to explain patterns in Nigeria's rice system and identify embedded strategies in the system.

Both applications of archetype analyses have the same goals of identifying recurring patterns and proposing strategies from the characteristics of the patterns (Eisenack et al. 2021). They allow for intermediate analysis between specificity and generalizability, bridging the gap between global narratives and local realities (Oberlack et al. 2019). Therefore, they both lend insights into the past to present state of rice systems.

7.6.3 The role of scenario planning

While Archetype analysis addressed the past to present state of rice systems in Chapters 2-4, scenario planning which is future-facing was applied in Chapters 5 and 6. Chapter 5's scenario planning began with deriving four plausible futures based on the shared socio-economic pathways with differences in rice yields, deforestation levels, land use demands and socio-economic trends.

In Chapter 6, scenario planning was applied in a horizon scanning activity as normative scenarios, that is, creating pathways and strategies to one desired sustainable rice future. This is also called backcasting (Kok et al. 2011). Both scenario studies include stakeholder opinions (23 stakeholders in co-production) although to a lesser extent in Chapter 5 (7 experts in expert consultation). Both explorative and normative scenario studies work towards developing strategies and making the future sustainable (Vervoort et al. 2014). Several studies have combined and argue for the use of both explorative scenarios and normative scenarios (Kok et al. 2011, Vervoort et al. 2014, Galli et al. 2016, Hebinck et al. 2018). Using both explorative and normative scenario planning highlight the challenges and opportunities in each explorative scenario towards a desired normative future As such I combined both kinds of scenario planning and at different scales - national (Chapter 5 – Vietnam) and worldwide (Chapter 6).

7.6.4 The integrative systems-thinking approach

Using multiple methods offers a promising methodological toolkit to integrate knowledge for sustainability advancement in rice systems. However, how knowledge is integrated across spatial, temporal or disciplinary dimensions is unclear in many studies. In my thesis, the methods are not all stand-alone methods but as explained, they have similar techniques and underlying goals. Methods involve trade-offs between specificity and generalizability, especially in different spatial and temporal scales but with the combination of 2 methods each under archetype analysis and scenario planning, the thesis is integrative in dimensions and scales. I chose the most appropriate methods depending on the context and objectives of each study. Integration is then carried out by a systems-thinking approach in all the research chapters and in synthesising the thesis.

The systems thinking approach goes beyond piecing together various studies on rice systems. Instead, the individual sub-systems are studied independently in the research chapters with systems thinking in mind (Chapters 2 - 6). This approach allows for specific and detailed insights from each sub-system, resulting in a cohesive understanding of rice systems (Chapter 7). The methodology presents an approach for the growing community engaged in transdisciplinary and interdisciplinary research and sustainability science within rice systems and the wider agricultural and food systems.

The ability of my methodological toolkit (Figure 1.1, Chapter 1) to organise thinking into different dimensions and scales has clear benefits which I have highlighted in sections 7.2 – 7.5 under methodological reflections. In the Introduction, I mentioned that the thesis followed guidelines to incorporate interactions, collaboration and foresight into sustainability research (Leemans 2016). As such, from the start of the thesis, I ensured that the methods chosen considered the system's interactions and interdependencies, allowed for diverse views of stakeholders to be included through co-production and collaboration and evaluated future outcomes through foresight. Admittedly, not all methods in my thesis reflect these three guiding principles (Table 7.1). But the methods together made up for each other's shortcomings in these aspects.

The grand challenges of rice production and sustainability and probably other crops require integrated collaborative efforts that yield immediate benefits and form the foundation for long-term interdisciplinary studies and transdisciplinary interactions. Such studies would identify systemic solutions that minimise tensions between food security, resilience and sustainability in agricultural and food systems.

The processes, dynamics and patterns that contribute to (un)sustainability do not result from (changes in) individual factors alone but also from the non-linear interactions of rice systems. The approaches applied in this thesis enhance an understanding of rice systems and provide a template and starting point for future integrated sustainability research of rice systems.

Furthermore, this methodology toolkit can be expanded to include other methods. Several sub-systems bring in more heterogeneity, requiring other methods not exploited in this thesis. For example, agent-based modelling could be considered to assess the consequences of the agents' behaviour in rice systems (Elsawah et al. 2015, Namany et al. 2020). I have not included this in my thesis to keep the overall research achievable within my PhD framework. Other methods require more data collection and analysis beyond my PhD's time frame. In addition, I have not studied all sub-systems and dimensions of rice systems. There is much more that can be done with several other methods. Future research should learn from the experiences gained from my thesis to apply multiple methods under broad techniques that cover different spatial and temporal scales and consider that complex systems are inherently interacting and interdependent, methods that look into the past and methods that allow us to learn about the future.

7.7 Conclusions

Rice systems face several challenges: the need to increase rice production, reduce GHG emissions, reduce irrigation-water usage and cultivate rice with less fertilisers and pesticides. We require rice systems to maintain or increase production levels while limiting its negative environmental impacts. Moreso, the farming communities and countries involved in rice production must adapt to climate change and protect their livelihoods and economic development. In many countries, rice is a staple food well traded internationally. All these lead to increased interdependencies between rice systems and their broader environments and between countries and continents.

Table 7.1: The methodological toolkit of my thesis, their strengths and weaknesses and how they reflect interactions and interdependencies, co-production and foresight in research

Chapter	Method	Interactions and inter-dependencies	Co-production	Foresight	Strength of method	Weakness of method
2	Cluster analysis	Factors that make up the dataset for analysis	-	-	Data-driven and allows for inter-mediate analysis between specificity and generalisation	No stakeholder input
3, 4	Fuzzy cognitive mapping	Fuzzy cognitive mapping and system archetypes	Stakeholder engagement	Multiple system states	Aggregates multiple perspectives in a specific context, describes causal relationships	Not spatially nor temporally explicit, generalises stakeholder knowledge into one system description
5	Land use modelling with iCLUE	Scenarios of social, economic and environmental developments	Expert consultation for developing scenario narratives	Multiple scenarios	Spatially explicit, quantitative	No causality
6	Horizon scanning	Experts from broad domain of rice research involved	Expert panel	Future research priorities	Multiple perspectives can be considered	Requires many rounds for adequate consensus

Over the past two decades, various food-systems shocks occurred, including the 2007/2008 global food crisis, the COVID-19 pandemic, the 2022 Russian invasion of Ukraine and the 2022 floods in India and Pakistan. Extreme weather shocks disrupt rice production, pandemics disrupt supply chains and policies limit rice trade. To cope with these food-systems shocks is challenging for all rice systems; hence, solutions are needed, beginning with understanding rice systems.

Many international research institutions are working to increase the scientific understanding of different rice systems. However, the knowledge of rice systems remains incomplete due to the fragmentation of rice research across scientific disciplines in which each discipline focuses on one or more specific sub-systems. For instance, geneticists concentrate on developing new rice varieties, agronomists aim to increase yields, hydrologists study irrigation infrastructure and water management and economists analyse rice prices and international market dynamics. This fragmentation hinders the integration of essential components required for a comprehensive understanding of rice systems.

The issues highlighted above motivated this thesis which takes a systems thinking approach to advance rice sustainability. My thesis is entitled 'Rice to Sustainability' depicting rice systems advancement to sustainability. I also use the word 'rice' as a homophone of the English word 'rise' and the Dutch word 'reis' (translated journey). Both homophones represent a journey and an upward or forward movement.

The sustainability journey requires integrating the essential components of rice systems through interdisciplinary research and the application of systems thinking. The contribution of my thesis is to emphasise that through the integration of distinct dimensions and factors (Figure 1.1 and Figure 7.1), rice sustainability is advanced as interacting and interdependent dynamic systems and not as independent, static systems. By demonstrating the application of systems thinking through all the research chapters, my thesis contributes a robust methodology for the growing community engaged in inter- and transdisciplinary research and sustainability science within agricultural and food systems.

I synthesised the research findings and visualised these findings in a system map (Figure 7.1). This system map presents key factors and their relationships leading to interactions, interdependencies and emergent system properties that contribute to (un)sustainability in rice systems. In addition, this map depicts possible pathways to sustainable rice systems. My thesis shows that rice systems, as well as other complex systems, can be analysed and captured into a system map. However, the system map is a product of research employing various methods spanning spatial and temporal scales. Similar studies analysing complex systems should adopt such systems thinking as conducted in my thesis.

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Supplementary material

Supplementary material Chapter 2

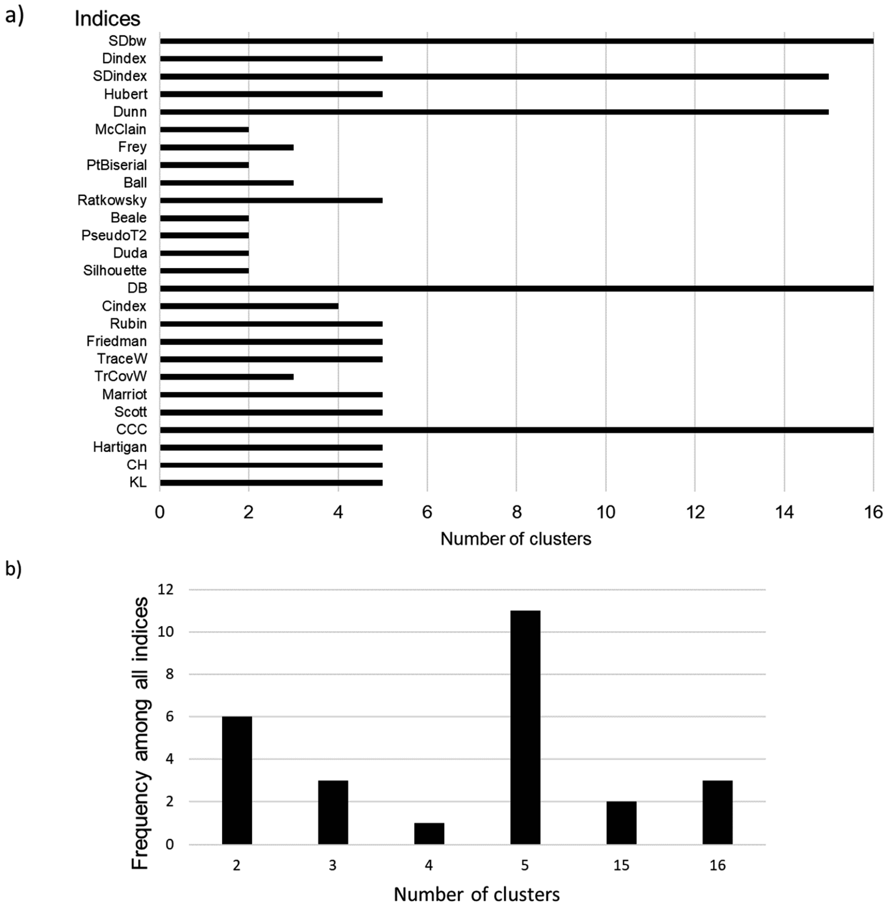


Figure SM2.1a. Different indices and their proposed optimal number of clusters. b) 11 out of 26 indices proposed 5 as the optimal number of clusters

Table SM2.2 : Sources and derivation of factors for the archetype analysis

Factors	Sub-factors	Data source	Formula
Land area equipped for irrigation as a percentage of agricultural area	Land area equipped for irrigation Agricultural area	FAOSTAT FAOSTAT	$\frac{Land\ area\ equipped\ for\ irrigation}{Agricultural\ area}\ x\ 100$
Yield gap	Attainable agro-ecological yield (kg/ha, converted to tons/ha)(for wetland rice high input) National average rice yield (kg/ha, converted to tons/ha)	GAEZ v4 FAOSTAT	$\frac{Attainable\ agroecological\ yield\ -\ national\ average\ yield}{Attainable\ agroecological\ yield}$
Share of suitable land area for rice (assessed as very suitable (VS)or suitable (S))	Total area extents for all agro-ecological zones and all management types (wetland-high input, wetland-low input; dryland-high input, dryland-low input) for current climate. Area extent assessed under suitability for all agro-ecological zones and all management types (very suitable area, suitable area and moderately suitable area, marginally suitable land, very marginally suitable, not suitable) for current climate	GAEZ v4 GAEZ v4	$\frac{(\sum very\ suitable + suitable\ area)}{\sum Extent}$
Per capita rice consumption (tons/person/year)	Per capita rice consumption (tons/person/year)	FAOSTAT World BANK	
Per capita rice production (tons/person/year)	Per capita rice production (tons/person/year)	USDA	$\frac{Rice\ production\ (tons)}{Population}$
Import Dependency Ratio (IDR)	Export quantity (tons) rice paddy milled equivalent Import quantity (tons) rice paddy milled equivalent* Per capita rice consumption (tons/person/year) Population (persons)	FAOSTAT FAOSTAT USDA World Bank	$\frac{Import\ quantity - Export\ quantity}{Consumption}$ where Consumption; $=Percapita\ rice\ consumption\ x\ population$
GDP per capita	GDP per capita (Current US$)	World Bank	

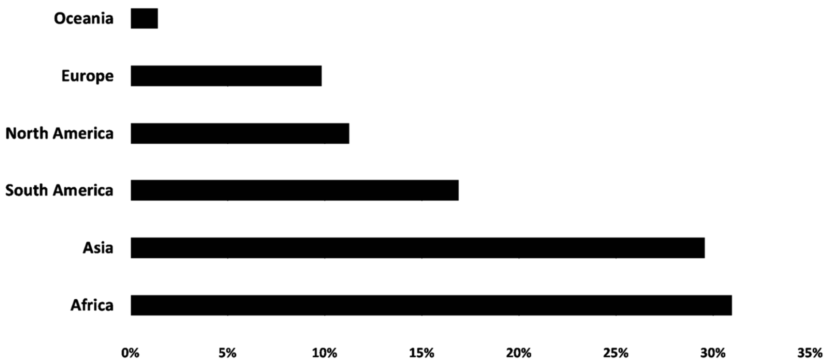


Figure SM2.3: Global spread of countries (n=71) included in the archetype analysis

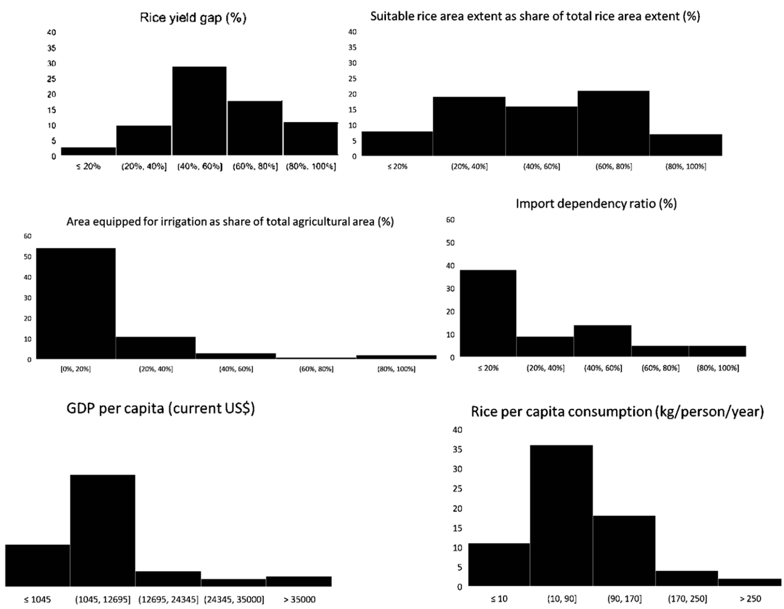


Figure SM2.4: Data distribution of factors in the dataset

Table SM2.5a: Dataset for cluster analysis

Country	YG	SUIT	EQIR	PCC	IDR	GDPPC
1. AFG	0.699308	0.167017	0.08451	15.8897	0.39902	502.1351
2. ARG	0.42097	0.890955	0.021322	11.6931	0.0085	12318.7
3. AUS	0.130172	0.680648	0.007093	14.1455	0.40944	53968.02
4. BGD	0.48926	0.771938	0.633579	220.0758	0.01421	1916.062
5. BEN	0.548402	0.22569	0.006152	69.5886	0.82227	1171.306
6. BTN	0.57458	0.121324	0.06414	147	0.53139	3195.878
7. BOL	0.710562	0.752444	0.01218	34.6795	0.04341	3382.11
8. BRA	0.403051	0.294513	0.03267	36.1407	0.0619	9166.545
9. BFA	0.763198	0.790089	0.004501	39.4997	0.58663	755.9657
10. KHM	0.590327	0.623774	0.047588	261.1305	0.00252	1452.525
11. CMR	0.865631	0.409202	0.002974	30.9424	0.70221	1500.26
12. TCD	0.85503	0.774954	0.000603	11.1989	0.06104	698.7724
13. CHL	0.421131	0.353049	0.070628	13.9283	0.48145	14781.32
14. CHN	0.268665	0.402553	0.140837	102.3167	0.01747	9240.133
15. COL	0.375563	0.330981	0.022491	37.1795	0.05336	6348.921
16. CRI	0.55342	0.464289	0.088096	49.7866	0.45076	12371.09
17. CIV	0.665658	0.150165	0.003443	103.1428	0.40656	2178.698
18. CUB	0.649974	0.921388	0.101333	67.1725	0.57606	8638.021
19. COD	0.905851	0.229226	0.00033	11.4131	0.11268	525.1958
20. DOM	0.498086	0.588166	0.126389	57.351	0.02154	7805.75
21. ECU	0.535301	0.349439	0.312557	55.7463	0.00013	6198.014
22. EGY	0.16459	0.755675	0.993245	43.646	0.04325	2880.095
23. FRA	0.547549	0.593217	0.093837	5	0.95145	39503.76
24. GMB	0.943923	0.499814	0.008264	96.2407	0.83684	718.9405
25. GHA	0.65177	0.363069	0.017606	43.6232	0.5252	2138.433
26. GRC	0.340019	0.706954	0.254996	5	0.17683	18849.2
27. GIN	0.863497	0.599764	0.006552	169.312	0.23057	898.8915

28.	GNB	0.846965	0.846455	0.030911	127.7471	0.38463	738.0572
29.	GUY	0.47018	0.240532	0.115151	202.6853	0.00016	6172.921
30.	HTI	0.681096	0.15892	0.052717	51.1186	0.74064	1362.89
31.	IND	0.615895	0.695782	0.395469	73.4957	0.00002	1945.931
32.	IDN	0.474378	0.172051	0.108814	137.9547	0.01936	3857.372
33.	IRN	0.547955	0.318981	0.2061	38.1473	0.36561	4837.063
34.	IRQ	0.561031	0.440729	0.381081	34.439	0.80737	5348.855
35.	ITA	0.409585	0.614205	0.322411	5	0.18362	32915.77
36.	JPN	0.215011	0.381818	0.544778	67.1524	0.05848	39598.66
37.	LAO	0.519409	0.289076	0.196497	276.7783	0.01751	2490.663
38.	LBR	0.858753	0.514668	0.001553	102.3157	0.5222	711.1516
39.	MDG	0.625255	0.645197	0.026556	112.7447	0.10512	508.9686
40.	MWI	0.822401	0.743866	0.016035	6.1872	0.04218	489.589
41.	MYS	0.512044	0.040943	0.051569	89.006	0.24603	10722.5
42.	MLI	0.586844	0.639851	0.009223	114.1708	0.06833	846.1483
43.	MEX	0.402724	0.449464	0.071972	7.3421	0.79616	9417.392
44.	MOZ	0.953502	0.372295	0.00286	27.5238	0.81761	475.1151
45.	MMR	0.583935	0.756494	0.177	190.7172	0.0001	1202.253
46.	NPL	0.644582	0.473349	0.332177	152.5301	0.1089	1080.365
47.	NIC	0.41072	0.830002	0.039289	58.1743	0.1761	2051.446
48.	NGA	0.834799	0.391322	0.004797	35.489	0.09505	2100.551
49.	PAK	0.66538	0.142976	0.543676	15.5286	0.00181	1582.893
50.	PAN	0.612385	0.616306	0.017061	73.8629	0.22103	15202.41
51.	PRY	0.405589	0.874854	0.008349	8.6831	0.00391	5542.46
52.	PER	0.16699	0.109491	0.105973	78.0135	0.0883	6724.27
53.	PHL	0.555862	0.262975	0.151534	128.7237	0.07558	3233.588
54.	PRT	0.444847	0.273847	0.149621	5	0.61701	22093.94
55.	KOR	0.275502	0.544353	0.427526	86.7072	0.06292	31561.26
56.	ROU	0.547783	0.784337	0.232716	5	0.66624	11413.48
57.	SEN	0.671017	0.233556	0.013517	116.2993	0.52921	1381.379

58. SLE	0.868151	0.498042	0.007597	168.0253	0.25478	513.461
59. ESP	0.332962	0.448588	0.149517	5	0.21692	28653.15
60. LKA	0.552013	0.690017	0.228502	137.5877	0.1018	3967.689
61. SUR	0.438576	0.640651	0.80826	134.7717	0.00167	6490.033
62. THA	0.70556	0.334285	0.281854	169.8852	0.00092	6925.114
63. TLS	0.661732	0.369463	0.102474	112	0.5511	1371.525
64. TGO	0.797321	0.412116	0.002068	48.422	0.55743	857.1932
65. TUR	0.316355	0.601708	0.137409	9.7185	0.268	10015.03
66. UGA	0.738349	0.671721	0.000773	4.7571	0.51652	763.1443
67. TZA	0.726855	0.679819	0.009335	41.4116	0.00031	1025.033
68. USA	0.224859	0.879216	0.066323	13.5718	0.12105	61420.39
69. URY	0.299896	0.908485	0.018405	11.9898	0.0029	17949.6
70. VEN	0.580622	0.566784	0.04907	22.3914	0.45021	16055.65
71. VNM	0.327369	0.343351	0.375285	226.0972	0.00155	3093.925

Table SM2.5b Dataset for time series analysis. Final archetype labels are for Cluster A – Laggards Archetype, B- Emergers, C- Midfielders, D – Grain and Water, E-Thrivers

GDP PER CAPITA

Cluster	Code	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2019
A	BEN	100.8736	114.4739	158.1382	279.3117	285.8333	339.9907	352.5394	438.4938	685.1623	1014.595	1178.966	1171.306
A	BOL	127.0737	196.0285	336.3411	695.4615	959.9032	682.3668	803.292	999.9691	952.4703	1603.276	2796.454	3382.11
A	CMR	132.1834	163.4182	270.7597	572.8802	757.859	1094.13	934.1777	751.9947	917.657	1325.656	1476.629	1500.26
A	TCD	117.4567	129.9994	165.6697	228.0138	185.4699	244.7074	240.8177	201.7649	364.8134	827.1276	945.6417	698.7724
A	GMB	104	104.4854	156.2536	288.5463	299.8319	289.5157	696.1913	661.767	512.3152	812.2343	694.8421	718.9405
A	GIN	383	383	383	383	383	383.8035	482.3474	452.3763	360.6426	635.0007	738.7368	898.8915
A	GNB	111	111.6888	124.2972	149.6577	184.7637	197.2476	232.1631	231.7999	373.3245	528.2621	636.2821	738.0572
A	HTI	74.33496	81.22242	98.96333	193.8831	276.8466	378.1016	338.4765	508.8546	683.6888	1053.986	1376.024	1362.89
A	LBR	306.8339	306.8339	306.8339	306.8339	306.8339	306.8339	306.8339	306.8339	287.4463	439.1021	696.2537	711.1516
A	MWI	49.31538	59.62376	92.69194	159.0039	176.6776	166.9397	178.3544	194.5861	257.6207	388.9818	405.3618	489.589
A	MOZ	205.6291	205.6291	205.6291	205.6291	205.6291	205.6291	205.6291	300.8326	344.9938	494.6979	636.0275	475.1151
A	SLE	144.0972	143.2466	190.4242	273.2023	296.2256	184.4675	185.454	171.3292	261.4274	377.0555	606.8961	513.461
A	TLS	415.0859	415.0859	415.0859	415.0859	415.0859	415.0859	415.0859	415.0859	494.901	613.5347	1147.18	1371.525
A	TGO	91.69301	124.5374	190.1679	327.0165	267.996	371.9842	339.6518	329.3108	367.6068	495.7598	598.4295	857.1932
A	TZA	193.8658	193.8658	193.8658	193.8658	193.8658	193.8658	174.3638	335.955	440.3363	632.8696	919.5404	1025.033
B	AFG	76.04579	142.6899	159.6388	243.4836	264.1112	264	264	264	205.8809	393.7331	604.9164	502.1351
B	BTN	316	316	316	316.3499	345.1461	494.7636	470.6886	650.3949	973.7786	1798.741	2595.958	3195.878
B	BFA	77.72974	83.93238	114.8964	220.6272	222.4114	303.5577	294.2606	258.1424	362.5401	584.7856	748.5632	755.9657
B	KHM	118.943	136.9978	94.38818	150	150	150	282.5304	297.9117	381.0196	688.0884	1020.595	1452.525
B	CIV	195.8827	261.4048	433.4302	1023.414	807.4282	901.8797	786.2903	1173.613	1174.125	1595.434	1898.972	2178.698
B	CUB	653	653.427	1074.398	1754.63	2206.874	2549.364	2365.581	2446.509	3243.297	4919.182	6860.42	8638.021
B	COD	242.7466	229.3922	360.9768	533.5668	370.8684	263.9375	208.9629	184.0812	182.9647	300.3937	450.7501	525.1958
B	IRQ	259.6711	319.1749	680.7543	2322.615	2916.144	4893.392	190.3038	1215.72	1383.487	3740.76	6256.825	5348.855
B	LAO	565.849	565.849	565.849	565.849	565.849	254.2884	292.5171	315.2373	380.6729	858.5059	1786.413	2490.663

B	MDG	139.5038	161.8289	233.0495	381.142	463.7956	326.7449	289.8939	304.5277	325.2961	450.6514	517.7161	508.9686
B	MLI	56.55372	56.55372	89.47815	191.0619	180.6443	267.6001	290.1583	285.105	393.5022	645.9194	804.2034	846.1483
B	MMR	23.67513	17.61395	27.07419	30.62575	35.3807	40.59191	73.60427	124.9254	166.1102	469.7697	1154.131	1202.253
B	NGA	107.8528	133.2531	292.5777	631.3791	1406.294	565.6552	395.9635	495.3412	880.7547	1998.209	2791.887	2100.551
B	ROU	1735.584	1735.584	1735.584	1735.584	1735.584	1735.584	1298.873	1664.52	2947.47	8262.98	9233.4	11413.48
B	SEN	324.9616	316.1779	415.0467	662.2912	624.8384	902.2419	825.3113	679.2639	817.2881	1241.922	1334.625	1381.379
B	UGA	76.34692	120.9265	176.9209	192.7565	186.3419	325.3939	198.0944	279.103	273.804	569.9808	832.7175	763.1443
C	CHL	639.5712	817.1894	1236.383	1632.345	1982.895	2017.617	3764.089	5348.944	5532.633	10694.83	14762.41	14781.32
C	CRI	351.6568	451.2765	744.9405	1565.503	1224.215	1652.225	2798.481	3532.475	4246.386	6652.152	10507.78	12371.09
C	DOM	237.3347	272.5049	508.2425	917.2747	1347.017	904.8063	1736.984	2586.106	2985.245	4899.921	6358.454	7805.75
C	ECU	391.0595	471.9459	720.0327	1677.982	2164.669	1466.028	1839.498	1965.998	2437.197	4002.19	5888.103	6198.014
C	FRA	1739.735	2535.002	4802.435	9511.423	10155.67	17402.17	23651.12	24635.26	28991.14	41194.58	41409.4	39503.76
C	GHA	218.412	233.3326	267.2452	339.5782	352.5803	389.3499	384.5343	371.6521	370.2906	1117.726	1856.891	2138.433
C	GUY	310.3434	357.4776	492.5387	661.5277	625.5796	544.4929	619.7164	949.7166	1017.951	3942.481	5352.098	6172.921
C	IRN	215.6315	321.3824	990.248	2274.216	3293.14	2718.628	1164.45	1777.577	2415.455	5341.19	6900.36	4837.063
C	MEX	423.0077	609.245	1052.98	1881.327	2719.237	2328.993	4653.048	5699.495	7595.047	9200.383	10343.18	9417.392
C	NPL	53.34185	72.00764	87.76468	114.3922	152.8842	181.9322	189.7107	215.3365	269.1624	455.8711	834.3836	1080.365
C	PAK	99.55171	147.2988	147.6586	242.2838	347.2208	361.97	441.5692	493.0572	622.9867	936.2415	1235.972	1582.893
C	PAN	579.1056	784.0468	1171.361	1781.355	2789.71	2696.803	3249.923	3877.747	4389.803	6865.501	11679.2	15202.41
C	PHL	215.3259	240.5378	311.2758	599.4912	746.1596	724.6994	992.579	1161.316	1088.114	1863.355	2795.432	3233.588
C	PRT	442.5573	734.1505	1648.57	2604.392	2857.871	5646.102	10212.58	11992.29	15462.71	22654.28	21357.6	22093.94
C	LKA	134.4028	161.8284	227.9303	245.4171	334.7877	415.4705	599.7811	826.6226	999.3947	1998.716	3564.941	3967.689
C	THA	120.6564	176.344	271.4648	527.6864	765.5467	1135.615	2238.335	2279.797	2380.552	4202.313	5862.58	6925.114
C	VEN	961.0242	930.4023	1549.537	2961.873	3944.662	2799.911	2941.418	3960.196	4358.169	10462.21	13702.16	16055.65
C	VNM	231.4523	231.4523	231.4523	231.4523	231.4523	315.6816	191.5796	354.7004	509.966	1146.136	2320.409	3093.925
D	BGD	101.2973	126.7067	161.4167	175.4252	226.4473	270.086	303.2637	406.2515	449.8358	637.2194	1018.813	1916.062
D	EGY	162.6085	190.1673	264.3181	396.0803	653.9095	747.941	791.3902	1269.496	1184.065	2017.304	3245.329	2880.095
D	IND	102.2438	101.2538	141.3756	208.7156	281.7846	343.7403	328.2076	422.8112	562.3843	1058.627	1506.218	1945.931

D	SUR	407.6398	667.1845	1004.479	1930.337	2435.884	2052.812	1201.069	2058.842	2645.308	6687.745	9101.3	6490.033
E	ARG	1114.637	1225.615	1950.093	2300.811	2968.686	3575.808	6883.974	7941.364	4507.832	8159.287	13027.13	12318.7
E	AUS	2022.373	2789.074	5141.49	8606.535	12019.05	14676.21	18712.97	21803.27	25546.49	44328.97	63595.47	53968.02
E	BRA	261.5045	380.8705	831.5223	1709.589	1684.515	2008.951	2955.694	4553.009	3499.59	8389.926	11768.56	9166.545
E	CHN	81.00285	101.1359	149.2221	177.2025	234.2022	289.2089	432.0283	830.4796	1350.469	3328.839	6917.571	9240.133
E	COL	294.9174	302.1162	451.6741	920.9347	1305.615	1240.938	1974.42	2548.871	2662.96	5091.531	7578.798	6348.921
E	GRC	717.2107	1207.686	2407.36	4714.233	5129.132	7453.256	11163.48	13194.34	17960.12	28471.86	21777.05	18849.2
E	IDN	68	68.22674	147.3383	365.2616	541.1003	502.7872	816.0446	823.2719	1025.526	2200.054	3556.933	3857.372
E	ITA	1106.123	1701.665	3182.028	5938.88	7748.467	15701.37	20788.19	21874.35	26755.17	37121.56	35013.87	32915.77
E	JPN	741.0756	1499.999	3648.427	7784.104	10582.52	22623.1	36028.62	36598.31	35745.18	39584.81	42448.01	39598.66
E	MYS	267.0498	333.3902	610.9085	1302.174	1980.706	2081.313	3451.631	4047.229	4616.048	7652.047	10692.24	10722.5
E	NIC	173.3706	306.812	443.4578	647.3475	757.2187	577.6773	578.1229	948.456	1056.756	1400.416	1842.364	2051.446
E	PRY	204.2008	222.9573	392.7137	931.561	1423.298	1120.266	1679.386	1833.44	1550.89	3452.89	5596.114	5542.46
E	PER	346.5546	500.2799	802.898	924.1457	1010.424	944.2978	1730.914	2116.342	2250.979	4051.937	6411.405	6724.27
E	KOR	115.7234	203.1587	442.6167	1358.978	2194.116	4713.039	9519.739	11402.53	15059.56	21882.28	27145.51	31561.26
E	ESP	605.95	1019.696	2255.658	4648.427	4839.804	9788.618	14630.25	15340.91	21064.54	31838.63	28862.34	28653.15
E	TUR	339.9759	502.801	753.0886	1578.194	1381.392	1955.629	2785.294	3830.344	5029.782	9736.232	11799.05	10015.03
E	USA	3417.278	4689.022	6691.382	10571.75	15862.37	21454.59	26506.85	33025.17	40093.94	47753.57	53405.62	61420.39
E	URY	657.1315	659.497	1175.066	2080.859	2356.128	2551.061	4765.164	7097.27	4669.409	8689.877	15765.54	17949.6

Table SM2.5c Dataset for time series analysis sorted by cluster Final archetype labels are for Cluster A – Laggards Archetype, B- Emergers, C- Midfielders, D – Grain and Water, E- Thrivers

Rice Yield

Cluster	Code	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2019
A	BEN	0.4446	0.91356	1.65158	1.4338	1.07398	1.30342	1.44528	1.9729	2.38056	2.94228	3.35922	3.577425
A	BOL	1.48584	1.62304	1.64298	1.5317	1.51674	1.82254	1.91246	2.01286	2.39846	2.27436	2.803	2.9109
A	CMR	0.90434	1.06408	0.88592	2.09714	3.65804	4.79316	3.27456	3.27384	1.57272	1.42632	1.27338	1.25535
A	TCD	1.131	1.14226	0.86066	0.87056	0.60894	1.72762	1.57788	1.3895	1.2138	1.24682	1.4901	1.425
A	GMB	1.27682	1.31394	1.29804	1.29742	1.7797	1.48058	1.49716	1.56392	1.839	1.14906	0.92904	0.54415
A	GIN	1.70196	1.70356	1.70518	1.70678	1.7084	1.71	1.7116	1.71322	1.73842	1.64924	1.19442	1.27295
A	GNB	0.74078	1.18716	0.85866	0.73446	1.0237	2.03678	1.959	1.51028	1.3542	1.87496	1.65726	1.557225
A	HTI	1.9067	2.07924	2.50266	2.47808	2.33398	2.2859	2.02794	2.26772	2.01754	2.19084	2.59382	2.9016
A	LBR	0.5409	1.10964	1.2278	1.23954	1.28058	1.19382	1.02884	1.2687	1.01442	1.32516	1.20192	1.078575
A	MWI	0.87948	0.88948	1.40656	1.54578	1.54736	1.56586	1.59894	1.74062	1.42636	1.90294	1.86566	1.76575
A	MOZ	1.49746	1.14476	1.4538	0.73458	0.83664	0.88222	0.6313	1.0185	0.676	0.5922	0.58748	0.479225
A	SLE	1.23202	1.40166	1.3896	1.37468	1.32974	1.33724	1.30066	1.2109	1.03136	1.57434	1.67888	1.16325
A	TLS	1.6517	1.79904	1.92584	2	2.00138	2.30202	2.6488	2.73216	1.51352	2.13746	2.99106	3.1924
A	TGO	0.9449	0.68504	1.1583	0.9949	0.67596	1.29764	1.35736	2.0243	2.11938	2.4175	2.09928	1.6586
A	TZA	1.32654	0.9417	1.4584	1.25672	1.29156	1.8818	1.62164	1.5845	1.80708	1.97948	2.01186	2.746625
B	AFG	1.60232	1.83588	1.94524	2.07602	2.23774	1.98618	1.91182	2.13302	2.65458	3.2598	2.61558	3.02095
B	BTN	2	2	2	2	2.03214	1.79312	1.44694	1.74746	2.31922	3.07758	3.68172	4.06495
B	BFA	0.74492	0.96946	0.9195	1.11924	1.69398	1.7502	2.01472	2.1904	1.8128	2.20946	2.1975	2.133525
B	KHM	1.0772	1.3163	1.29388	0.9975	1.22822	1.37104	1.46012	1.88588	2.10882	2.73252	3.16236	3.560675
B	CIV	0.881	1.11482	1.24156	1.17168	1.16616	1.16688	1.11092	1.56842	1.93888	2.07344	2.4307	2.72025
B	CUB	1.53138	1.77506	2.02214	2.98136	3.37204	3.17468	2.35942	2.7285	3.2502	2.85228	3.2846	3.516525
B	COD	0.7378	0.78894	0.76602	0.78352	0.83156	0.80364	0.74252	0.75498	0.755	0.7554	0.75816	0.83275
B	IRQ	2.75016	2.90092	2.46866	3.0194	2.73654	2.8944	2.02358	1.71898	2.51192	3.07542	4.48434	4.38995
B	LAO	0.84248	1.10738	1.28706	1.2884	1.74736	2.2093	2.4467	2.80318	3.26254	3.70376	3.94964	4.273125

B	MDG	1.85346	1.8036	1.86544	1.77848	1.7644	1.99	2.0839	2.11608	2.35894	3.1547	3.99584	3.68205
B	MLI	1.05244	0.94838	0.90956	1.15464	0.99492	1.35498	1.68418	2.04218	2.16622	2.77508	3.13922	3.395425
B	MMR	1.64406	1.64224	1.73836	2.21398	3.06578	2.96628	2.95634	3.13932	3.49722	3.91928	3.80714	3.8231
B	NGA	1.1466	1.36404	1.67014	1.70928	2.06352	2.0961	1.78268	1.58866	1.38002	1.66136	1.9054	1.483
B	ROU	2.9807	2.57536	2.33192	2.285	2.9098	2.37852	2.81036	2.69	2.63222	4.4052	4.48344	4.971675
B	SEN	1.29868	1.24676	1.13874	1.24574	1.893	2.057	2.31474	2.44138	2.52204	3.12212	3.9371	3.50145
B	UGA	1.20288	1.07138	0.88852	1.22166	1.26888	1.29982	1.38236	1.41288	1.4672	1.80264	2.43782	2.71615
C	CHL	2.73372	2.55882	2.92316	3.23918	3.74552	4.11062	4.2633	4.34102	4.90742	5.16484	6.11156	6.46485
C	CRI	1.36906	1.72672	2.15732	2.68828	2.8328	3.50532	4.28188	4.14544	3.53118	3.86478	3.91974	4.346025
C	DOM	2.04662	2.2657	3.16474	3.17798	4.30452	4.53322	5.64534	4.57462	4.58052	4.67516	4.96752	5.140975
C	ECU	2.13356	2.31816	2.78404	2.86946	2.98092	2.98452	3.29972	3.51186	3.89296	4.19166	4.16416	3.99235
C	FRA	3.9137	3.96064	3.60342	3.50128	4.72112	5.46306	4.99352	5.77856	5.61954	5.33094	5.02816	5.26215
C	GHA	1.0462	1.18178	0.96934	0.86062	0.90898	1.30994	1.86086	1.87194	2.1513	2.2197	2.59446	2.834125
C	GUY	2.07384	1.81142	2.04364	2.53668	3.1714	3.20832	3.5715	3.94556	4.11964	4.3716	4.19306	4.2057
C	IRN	2.711	2.7383	3.08218	3.46374	3.35226	3.51918	3.99208	4.16822	4.37388	4.16076	4.1665	4.875125
C	MEX	2.28732	2.54176	2.7233	3.22436	3.6213	3.62066	4.45206	4.42904	4.56874	4.6883	5.53292	6.293925
C	NPL	1.95844	1.87888	1.94728	1.82482	1.89476	2.18198	2.25108	2.49816	2.74718	2.73448	3.24344	3.44745
C	PAK	1.41568	1.88204	2.31732	2.37888	2.51206	2.39344	2.52274	2.93438	2.97882	3.32752	3.66024	3.157675
C	PAN	1.09152	1.24438	1.46896	1.61016	1.95796	2.21244	2.201	2.56884	3.00076	2.861	3.04566	3.614325
C	PHL	1.25742	1.49848	1.54258	2.03196	2.4545	2.73352	2.84864	2.90044	3.3873	3.69338	3.8615	3.97295
C	PRT	4.52648	4.56668	4.0379	3.97566	4.4264	4.39102	5.34532	5.96006	5.75126	5.78206	6.00388	5.774775
C	LKA	1.9074	2.23462	1.99254	2.27706	2.90856	3.06376	3.07256	3.31936	3.51588	3.82296	3.75576	3.863425
C	THA	1.77402	1.8484	1.86962	1.81998	2.0006	2.05086	2.2491	2.44876	2.9257	2.97836	3.08574	2.9978
C	VEN	1.67656	1.92798	2.45492	3.05802	2.70386	3.38488	4.25512	4.68578	4.8806	4.96524	5.05172	3.744975
C	VNM	1.98316	1.87494	2.18158	2.02282	2.57032	2.97156	3.4369	3.99828	4.65174	5.13872	5.65194	5.694125
D	BGD	1.67788	1.69116	1.71282	1.91256	2.10364	2.3642	2.6505	3.02786	3.55726	4.13282	4.4868	4.678525
D	EGY	5.29274	5.08074	5.29844	5.44804	5.67194	6.28274	7.7747	8.66536	9.64928	9.71842	9.52886	8.942275
D	IND	1.47966	1.55026	1.69482	1.84008	2.09034	2.43628	2.72566	2.87556	2.99582	3.2629	3.61144	3.9135

D	SUR	2.86804	3.47624	3.53426	3.935	3.9601	3.82562	3.69258	3.81216	3.70846	4.20286	4.39136	4.68535
E	ARG	3.50832	3.79496	3.65612	3.32376	3.68578	4.06528	4.58446	5.15262	5.8304	6.6196	6.67472	6.6666
E	AUS	6.29052	7.23032	6.3104	5.647	6.61812	7.30376	8.45426	8.30494	8.41404	8.90554	9.85292	9.81665
E	BRA	1.61164	1.48482	1.45704	1.4446	1.61294	1.91174	2.3365	2.80352	3.34794	4.09378	5.1285	6.012025
E	CHN	2.55974	3.1807	3.4029	3.89194	4.98886	5.4544	5.82942	6.30278	6.19676	6.48266	6.7772	6.967325
E	COL	1.98114	2.61112	3.98648	4.24016	4.42632	4.54562	4.11102	4.59376	4.7687	4.63606	4.45142	5.5348
E	GRC	4.03168	4.92478	4.94454	4.62914	5.79844	6.37008	7.28644	7.35238	7.19212	7.46342	8.30826	7.908225
E	IDN	1.76084	2.05976	2.54182	2.94834	3.7861	4.1352	4.35202	4.3398	4.502	4.84384	5.16476	5.120775
E	ITA	5.08378	4.77394	5.15302	5.00188	5.64702	5.82618	5.76432	6.0618	6.29428	6.40242	6.4972	6.78935
E	JPN	5.01174	5.54734	5.83066	5.78762	5.93136	6.1787	5.96524	6.45838	6.42616	6.53108	6.85928	7.065525
E	MYS	2.0967	2.20782	2.59968	2.72152	2.67808	2.60562	3.01354	3.0414	3.29126	3.57172	3.68562	3.7496
E	NIC	1.94574	2.7382	2.96394	3.09072	3.77226	2.90236	3.33688	3.42166	3.2269	4.2538	5.02676	6.271525
E	PRY	2.41714	2.3084	2.06028	1.89698	2.14698	2.44736	3.77316	3.9418	3.71584	3.9934	5.96898	6.525
E	PER	4.0529	4.04356	4.17084	4.27296	4.57676	5.01866	5.40878	6.0865	6.70262	7.10828	7.6556	7.6697
E	KOR	4.11152	4.31088	4.93694	6.07792	6.20228	6.31848	6.03742	6.69756	6.50782	6.66684	6.76784	7.035575
E	ESP	6.21524	6.17224	6.02918	6.07296	6.02024	6.23104	6.2965	7.09678	7.23828	7.21938	7.77858	7.637075
E	TUR	4.07724	4.01416	4.36086	4.74568	4.49124	5.06018	5.00612	5.33066	6.38228	7.59474	7.99486	7.97015
E	USA	4.3612	4.9811	5.08656	5.05968	5.4913	6.27706	6.40292	6.6863	7.47738	7.79498	8.35466	8.381
E	URY	3.23718	3.46926	3.92384	4.08416	5.04196	4.76182	5.02596	6.1811	6.36856	7.63464	8.17144	8.15485

Table SM2.5d Dataset for time series analysis sorted by cluster. Final archetype labels are for Cluster A – Laggards Archetype, B- Emergers, C- Midfielders, D – Grain and Water, E- Thrivers

Import dependency Ratio

Cluster	Code	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2019
A	BEN	0.837018	0.717021	0.463541	0.435185	0.829457	0.871986	0.951401	0.738745	0.763955	1.069667	0.826767	0.822266
A	BOL	0.051836	0.006276	0.006897	0.000282	0.099294	0.014934	0.005287	0.009014	0.012765	0.037511	0.064993	0.043413
A	CMR	0.412796	0.331784	0.538674	0.30222	0.313664	0.507556	0.732805	0.716687	0.85797	0.815686	0.76005	0.702206
A	TCD	0.007964	0.000909	0.006462	0.078747	0.304219	0.189917	0.125504	0.007425	0.019483	0.020189	0.01275	0.061038
A	GMB	0.206584	0.235992	0.262142	0.50825	0.572027	0.70387	0.766934	0.750954	0.738113	0.698319	0.632334	0.83684
A	GIN	0.124998	0.079558	0.067317	0.121392	0.113667	0.178968	0.223041	0.15396	0.166643	0.160001	0.183404	0.230571
A	GNB	0.100525	0.23419	0.396502	0.293187	0.189174	0.262354	0.334767	0.382391	0.468415	0.227874	0.281431	0.384633
A	HTI	0.000689	0.000112	0.009334	0.162184	0.101212	0.232575	0.572315	0.646543	0.734949	0.748446	0.740211	0.740639
A	LBR	0.20623	0.204887	0.156993	0.20283	0.242877	0.252191	0.588515	0.202351	0.473553	0.457085	0.460422	0.522202
A	MWI	0.025217	0.029918	0.000996	0.011666	0.003854	0.034872	0.065461	0.018934	0.054202	0.035531	0.008661	0.042183
A	MOZ	0.010109	0.00955	0.01288	0.554389	0.508973	0.438279	0.507796	0.225072	0.621772	0.74423	0.739233	0.817608
A	SLE	0.035743	0.063733	0.042782	0.061514	0.107071	0.168523	0.272049	0.32482	0.168236	0.129313	0.190526	0.254782
A	TLS	0.674104	0.686086	0.618403	0.49821	0.384913	0.369582	0.26178	0.386421	0.354477	0.135454	0.435438	0.551018
A	TGO	0.127937	0.123288	0.133658	0.444677	0.578682	0.553834	0.354352	0.421772	0.550417	0.44808	0.428364	0.557431
A	TZA	0.101435	0.108497	0.123438	0.129195	0.176143	0.091914	0.107515	0.141577	0.115986	0.039206	0.055586	0.00031
B	AFG	0	0	0.001479	0.013665	0.016807	0.011143	0.140278	0.241694	0.330959	0.15261	0.218968	0.399023
B	BTN	0.048548	0.048443	0.047619	0.045839	0.122201	0.220553	0.354951	0.370018	0.298354	0.33151	0.405332	0.531387
B	BFA	0.086088	0.059591	0.085397	0.301778	0.548965	0.67201	0.639879	0.641676	0.669002	0.532756	0.550635	0.586627
B	KHM	0	7.76E-05	0.05877	0.059454	0.055807	0.027642	0.024398	0.012461	0.012693	0.005543	0.00597	0.00252
B	CIV	0.18295	0.152563	0.168813	0.226886	0.435631	0.36278	0.3437	0.408386	0.523656	0.539695	0.411843	0.406556
B	CUB	0.57194	0.50466	0.390899	0.280696	0.286126	0.300267	0.47279	0.398766	0.483117	0.541511	0.491924	0.576061
B	COD	0.293149	0.142028	0.118913	0.143935	0.10896	0.186018	0.140471	0.158048	0.304077	0.239142	0.087319	0.112684
B	IRQ	0.265555	0.010584	0.365073	0.626163	0.758508	0.735681	0.589732	0.773317	0.812938	0.800233	0.786433	0.80737
B	LAO	0.155723	0.076199	0.063561	0.091766	0.022743	0.00304	0.010225	0.011635	0.010358	0.010352	0.002939	0.017512

B	MDG	0.010984	0.008678	0.03362	0.048661	0.092822	0.04007	0.018669	0.03367	0.061648	0.035975	0.065289	0.105116
B	MLI	0.00021	0.042333	0.172747	0.092982	0.312712	0.189359	0.059605	0.091528	0.166453	0.090155	0.075936	0.068329
B	MMR	0	1.07E-06	1.75E-07	0	0	0	0	0.000218	0.000507	0.000769	0.000544	0.000101
B	NGA	0.006142	0.003398	0.007881	0.406343	0.274595	0.115386	0.099492	0.166188	0.314723	0.242108	0.2553	0.095054
B	ROU	0.422673	0.333594	0.48188	0.539594	0.396893	0.222768	0.637143	0.896565	0.953079	0.608903	0.66493	0.666236
B	SEN	0.578665	0.572044	0.658682	0.741451	0.734827	0.696926	0.694231	0.726173	0.806437	0.73286	0.698706	0.529207
B	UGA	0.681475	0.494242	0.204072	0.200451	0.2607	0.099945	0.053679	0.296083	0.282205	0.308869	0.429239	0.516525
C	CHL	0.125466	0.291213	0.3001	0.134681	0.111218	0.143671	0.261827	0.41915	0.419615	0.487715	0.459845	0.481446
C	CRI	0.016235	0.053009	0.030179	0.000429	0.041991	0.061054	0.154631	0.194231	0.318489	0.286514	0.258051	0.450756
C	DOM	0.122553	0.014354	0.122912	0.087261	0.031894	0.084054	0.034339	0.095037	0.055169	0.034232	0.033753	0.021538
C	ECU	0.005139	0.005241	9.02E-05	0.030499	0.051796	0.01716	0.000469	0.017262	0.000212	0.000209	0.006151	0.00013
C	FRA	0.365052	0.614527	0.725466	1.011019	0.988677	0.865357	0.834236	0.883134	0.972529	0.931456	0.936941	0.951446
C	GHA	0.469447	0.430424	0.314822	0.25944	0.375784	0.49322	0.528605	0.268055	0.673418	0.544127	0.554056	0.525199
C	GUY	0	0.000311	0.000395	0	0	0	0	6.29E-05	0.000582	0.000162	0.000111	0.000164
C	IRN	0.018801	0.013612	0.092243	0.205302	0.246296	0.234068	0.27435	0.246201	0.262697	0.310797	0.375011	0.365612
C	MEX	0.013184	0.017561	0.044028	0.052849	0.138226	0.118145	0.399459	0.461716	0.649567	0.682048	0.765908	0.796159
C	NPL	0	0	0	0	0.008149	0.004777	0.010542	0.017497	0.009333	0.03161	0.074168	0.108902
C	PAK	0.000225	1.6E-05	0.003811	1.69E-06	1.48E-06	6.71E-05	0.000639	0.00018	0.001297	0.000531	0.003994	0.001807
C	PAN	0.020158	0.001078	0.035879	0.000198	0.00048	0.000602	0.004197	0.057496	0.045433	0.14253	0.196242	0.221026
C	PHL	0.061755	0.016271	0.051761	0.002403	0.017764	0.019393	0.009391	0.090186	0.077283	0.111648	0.045331	0.075576
C	PRT	0.075087	0.133729	0.150672	0.357849	0.407156	0.339242	0.479165	0.396859	0.41567	0.401304	0.426955	0.617006
C	LKA	0.348112	0.236479	0.201657	0.14339	0.04963	0.068542	0.044485	0.071784	0.031649	0.02505	0.046194	0.061563
C	THA	0	0	0	0	0	0	1.07E-06	3.71E-05	0.000118	0.000376	0.000712	0.000921
C	VEN	0.030571	0.015132	0.008093	0.000447	0.001628	0.042714	0.025153	0.004079	0.02028	0.134429	0.241477	0.450219
C	VNM	0.029598	0.11191	0.064243	0.015459	0.012355	0.012637	0.000189	5.04E-05	0.000296	3.18E-05	0.000512	0.001554
D	BGD	0.019627	0.022264	0.021	0.014537	0.013729	0.011477	0.008205	0.030656	0.021024	0.01188	0.013809	0.014214
D	EGY	1.32E-06	3.58E-06	2.39E-06	0	1.19E-05	0.004554	0.000551	0.00036	0.004128	0.010978	0.017086	0.043247
D	IND	0.015309	0.01343	0.004577	0.001518	0.001989	0.00251	0.000344	8.71E-05	2.45E-06	7.98E-07	8.1E-06	2.36E-05

D	SUR	0.001947	0.000412	0	0.000294	0	0	0	0.000362	0.001887	0.001062	0.004496	0.001666
E	ARG	0	0.000105	0	0.017252	0.003718	0.000805	0.016007	0.018859	0.019933	0.010174	0.006059	0.008503
E	AUS	0.010552	0.011823	0.00229	0.00408	0.012354	0.054238	0.056697	0.065995	0.116121	0.500565	0.240152	0.409445
E	BRA	3.51E-06	5.46E-06	0.002276	0.022699	0.020605	0.040777	0.073311	0.086128	0.05908	0.051935	0.049731	0.061905
E	CHN	0.007191	0.00416	0.003662	0.003597	0.003482	0.005048	0.004978	0.00366	0.004914	0.004766	0.012934	0.017469
E	COL	0.014645	0.000342	2.57E-05	0.006959	0.000123	0.004432	0.054816	0.065561	0.033973	0.041117	0.057903	0.053359
E	GRC	0.047315	0.037436	0.049427	0.00467	0.074846	0.051543	0.053729	0.060034	0.111515	0.178452	0.135795	0.176833
E	IDN	0.06704	0.032101	0.044461	0.065868	0.013614	0.002047	0.019001	0.043126	0.017313	0.010698	0.022056	0.019357
E	ITA	0.003141	0.010077	0.020427	0.241553	0.345412	0.160662	0.064678	0.090966	0.108869	0.155876	0.14072	0.183621
E	JPN	0.0264	0.018869	0.002279	0.002095	0.004864	0.001327	0.014989	0.043946	0.060007	0.05582	0.058443	0.05848
E	MYS	0.27923	0.189619	0.112277	0.120544	0.178623	0.136532	0.162643	0.226984	0.183523	0.284407	0.28679	0.246027
E	NIC	0.126296	0.107458	0.001877	0.099478	0.090018	0.260077	0.188258	0.207234	0.260515	0.223559	0.187215	0.176101
E	PRY	0	0	0	0.00277	0.00016	7.15E-06	0.004404	0.023833	0.030281	0.008996	0.003594	0.00391
E	PER	0.084384	0.067534	0.030002	0.170512	0.077943	0.14872	0.238639	0.140862	0.029062	0.033569	0.068479	0.088295
E	KOR	0.004893	0.060746	0.082823	0.032583	0.070716	0.000145	0.000168	0.013398	0.019309	0.040912	0.069641	0.062922
E	ESP	0	0.003619	8.33E-05	0.001127	0.107015	0.227247	0.330781	0.159112	0.135726	0.14479	0.125224	0.216924
E	TUR	0.010635	0.029874	0.110366	0.073287	0.128189	0.352663	0.522668	0.462602	0.383338	0.25537	0.236116	0.268002
E	USA	0.004942	0.002263	0.006605	0.000398	0.006406	0.026176	0.036511	0.050735	0.060923	0.089341	0.10311	0.121054
E	URY	3.86E-05	0.000429	3.57E-05	0.01313	0	0.008228	0.014383	0.001838	0.002053	0.000929	0.002472	0.0029

Table SM2.5e Dataset for time series analysis sorted by cluster. Final archetype labels are for Cluster A – Laggards Archetype, B- Emergers, C- Midfielders, D – Grain and Water, E- Thrivers

Production per capita

Cluster	Code	1961-1965	1966-1970	1971-1975	1976-1980	1981-1985	1986-1990	1991-1995	1996-2000	2001-2005	2006-2010	2011-2015	2016-2019
A	BEN	0.379126	0.848004	2.760358	3.714253	1.832943	1.974148	2.211812	5.141973	8.35788	11.83022	24.76074	31.30724
A	BOL	11.00065	15.65844	19.15936	18.60537	19.63278	27.55079	32.92758	35.91492	40.87865	40.93404	44.67716	44.85769
A	CMR	1.819093	2.581545	2.475121	6.451382	8.087132	5.94238	2.956994	3.438092	3.122056	5.051119	8.856327	12.3832
A	TCD	8.996598	10.29294	10.7305	7.52634	4.439196	9.815649	12.85649	14.41623	13.02159	12.60326	19.37652	17.55931
A	GMB	84.53498	77.8769	59.28702	44.84109	43.01727	26.9756	17.2505	18.46686	17.21465	30.04307	29.64905	14.28114
A	GIN	62.65469	71.23905	81.46005	93.58557	105.0594	113.4882	122.2455	133.2943	131.1216	150.6451	179.2984	189.0275
A	GNB	76.1956	59.11578	50.49175	67.75067	114.8362	117.1307	122.1282	85.70407	69.84995	105.9807	107.8919	96.46448
A	HTI	15.53656	17.43121	21.01926	21.33376	20.03207	18.67241	15.06545	15.58348	11.88059	12.8263	14.19827	15.43739
A	LBR	104.7163	117.714	146.5268	142.0438	139.9424	127.5005	37.90226	67.27716	40.22716	70.43243	67.00101	58.4321
A	MWI	1.472814	3.154603	10.81802	12.00354	4.964729	4.350095	5.055645	7.025847	6.132723	8.219562	7.547195	6.258882
A	MOZ	12.17061	9.957882	11.38746	5.594297	6.617429	7.285333	5.044722	10.41178	5.590314	6.420743	6.903125	5.321522
A	SLE	138.1535	172.7304	172.0535	173.9571	133.6642	121.2551	102.9686	71.89387	92.84858	138.5897	163.6314	120.1461
A	TLS	27.4069	26.93404	30.63235	44.51984	58.11339	58.68431	64.96939	48.84261	56.43334	80.90919	80.92931	52.29979
A	TGO	12.53896	9.753475	6.845644	5.978811	4.877837	6.957187	9.871716	17.02591	12.54671	15.2982	23.6382	18.28638
A	TZA	10.96915	9.502881	15.3142	18.43121	16.11151	27.48307	20.76775	23.26884	28.39429	37.63427	40.8063	51.85365
B	AFG	35.89818	35.82137	33.44506	32.17368	27.94017	27.97243	21.28605	17.57809	16.86492	21.72284	16.44665	9.732542
B	BTN	161.8446	157.7392	149.8023	141.2805	137.9646	106.8071	80.09554	84.38276	77.66189	107.9727	110.4862	94.78116
B	BFA	6.338804	6.980412	5.953437	6.426077	5.972131	4.488071	5.892751	8.903264	7.335482	11.55782	17.97024	18.46551
B	KHM	398.1	423.3436	203.0653	153.4451	238.1654	273.3239	253.4452	317.1842	353.8956	517.5387	613.8157	654.6975
B	CIV	55.92653	67.99127	66.13247	65.34532	49.10996	55.83325	50.73596	40.18439	37.78833	39.50133	76.98814	81.5812
B	CUB	22.62393	19.8699	41.15033	46.68756	51.58654	48.82138	32.89151	49.67553	51.09219	41.42179	51.12976	39.06612
B	COD	3.771888	7.626382	9.103615	8.827414	9.58886	10.78223	10.44624	7.673227	6.170899	6.599397	11.71435	15.02644
B	IRQ	17.2099	29.15212	16.15945	13.40461	9.411434	11.23263	13.29086	9.677101	7.960497	9.452114	9.478501	6.781354
B	LAO	266.7171	322.6335	296.9135	251.2212	346.1307	326.0212	301.9086	350.978	438.1032	481.0993	551.5403	546.9189

B	MDG	284.61	284.771	271.9986	247.6272	219.5434	207.2096	191.7313	169.7667	167.2609	202.0503	176.1752	151.1069
B	MLI	31.63042	27.27072	27.66311	28.06043	21.88533	33.39911	49.18407	65.25595	70.70746	94.19697	124.8082	157.4194
B	MMR	334.3219	296.1149	286.4513	323.1408	391.602	343.3241	370.8821	401.782	487.5516	631.4007	516.2808	495.1827
B	NGA	4.300709	5.980952	7.791434	8.440671	16.35718	24.32108	29.10431	27.92339	23.73285	25.82697	31.49365	41.63749
B	ROU	2.145398	3.214985	2.713054	2.195647	3.744479	4.663894	1.28136	0.410134	0.200984	2.233213	2.657902	2.166809
B	SEN	28.46472	28.36678	18.88692	18.39321	20.87416	21.78268	20.92453	21.52352	20.6411	31.12741	39.88666	68.92561
B	UGA	0.425284	0.745605	1.52699	1.855292	1.388961	1.97841	3.71647	4.075658	4.912189	6.001041	6.34842	5.106779
C	CHL	9.809096	7.776176	6.229236	10.79373	11.18562	11.77258	9.463577	7.238085	8.367037	7.365403	8.057347	9.000447
C	CRI	47.95367	53.4457	60.3403	84.86993	81.87031	61.97766	58.09842	66.00778	46.7058	50.21359	48.08598	34.90636
C	DOM	35.67846	43.81235	46.26	62.89162	75.67396	66.75217	62.05441	63.36817	74.31156	81.82064	80.91346	86.23281
C	ECU	45.45505	40.9513	37.60222	42.41955	44.73399	82.15187	100.3585	106.0188	109.407	109.5693	96.61959	74.72948
C	FRA	2.480929	1.917987	1.050844	0.536187	0.649151	1.460161	2.131253	1.949936	1.70955	1.741924	1.516785	1.219673
C	GHA	4.637785	6.362302	6.974485	8.637778	5.290433	5.732779	9.950339	11.591	12.75212	13.61772	20.68164	26.29924
C	GUY	367.8702	315.8551	296.4537	352.408	354.5059	302.2922	470.8747	701.7102	645.8291	681.7403	899.2924	903.8863
C	IRN	35.77204	37.87024	40.7567	39.30976	35.34604	33.42502	38.78556	37.98515	38.39949	33.2268	29.77001	27.68809
C	MEX	7.570815	8.005314	8.566116	7.372217	8.0904	6.245905	3.994881	4.3123	2.511302	2.4195	1.680501	2.089737
C	NPL	202.2997	186.7566	183.7569	160.8269	157.0251	171.598	154.0598	165.7702	168.9759	155.8899	177.0135	181.608
C	PAK	37.60817	51.347	56.86267	62.58303	57.39658	48.67759	45.4285	51.73801	46.46452	51.8715	50.88141	43.09272
C	PAN	97.91201	104.7313	94.77527	87.40452	87.9316	81.98304	79.87593	75.04027	104.2539	83.72815	71.15062	82.04706
C	PHL	136.5447	142.3652	137.2344	161.8958	157.0918	156.8037	148.024	148.0358	165.7084	176.9772	182.6042	176.5296
C	PRT	18.56415	18.61346	17.29635	13.08749	12.96101	14.6205	12.13423	15.59577	13.81382	14.92438	17.29576	16.29617
C	LKA	91.4324	108.2957	102.4095	121.6985	151.8403	139.8835	142.7733	136.7785	150.7809	183.0194	199.2489	177.8909
C	THA	375.8147	369.9445	347.3603	350.3537	375.8292	351.695	349.1917	386.1769	454.9511	488.7181	509.048	453.5461
C	VEN	14.83076	21.15224	20.30755	33.58722	32.08139	21.1934	32.70076	31.58976	31.90828	38.18974	34.49547	19.76104
C	VNM	265.7609	218.4742	230.4255	212.583	250.3327	264.6484	311.147	376.92	420.5619	439.1048	485.2591	456.0867
D	BGD	287.4335	272.3942	247.6086	255.6526	250.664	250.535	241.5122	257.1545	279.5833	317.0154	335.5465	332.6123
D	EGY	63.70958	71.00232	65.03325	57.21089	49.95277	47.96855	69.5989	80.46711	82.29403	77.44197	62.5731	46.81027
D	IND	110.2096	107.1926	108.3731	109.7171	112.9611	120.1973	124.9727	125.0162	115.7017	118.5825	123.2133	127.1594

D	SUR	264.5505	333.1104	417.7512	609.6271	798.5994	667.4827	534.4655	424.7815	361.1771	386.4432	462.243	486.7311
E	ARG	8.970032	12.15556	12.03083	11.22309	13.23983	13.33139	18.90449	31.95778	22.64339	30.42252	38.03565	29.90311
E	AUS	12.78601	19.10558	24.56824	38.11797	47.36577	44.93931	57.44718	65.7873	42.28798	13.76428	37.37607	18.04898
E	BRA	77.44831	73.36122	68.50663	75.53462	67.65037	71.34266	65.45498	55.92219	63.1072	60.98058	61.00143	54.24996
E	CHN	105.0896	125.9516	136.2262	141.1172	160.4767	160.702	154.3127	158.1386	135.466	143.506	150.7777	151.1386
E	COL	32.58131	35.07413	54.52199	64.94256	64.01036	58.80083	48.2806	51.05584	54.67618	49.56082	47.32149	62.49215
E	GRC	10.31907	10.46015	9.751532	9.013886	9.213184	11.70557	14.26869	17.55692	14.85058	17.74805	22.0797	22.71351
E	IDN	130.4407	148.9604	170.3731	182.1757	226.1337	241.5103	248.9225	245.521	238.0825	241.944	236.867	209.5718
E	ITA	11.94588	13.87645	17.11399	16.34969	17.8716	20.58864	22.85852	24.3113	24.32478	25.47455	24.71732	25.47498
E	JPN	171.4303	175.8149	144.2581	130.9295	114.0494	108.2731	101.6448	94.98521	85.33003	84.21519	86.59821	84.42156
E	MYS	128.6402	138.1797	167.5917	145.2745	121.089	101.8416	105.7659	94.88349	90.09158	87.33217	83.93636	82.31896
E	NIC	22.91636	32.27583	30.56379	28.64423	44.87692	28.87635	40.50783	51.83101	53.34276	58.54133	64.01877	67.95361
E	PRY	9.020443	10.16567	17.56504	18.75068	20.40587	21.08771	13.00194	18.25753	19.48681	30.42074	94.20473	135.3815
E	PER	29.65074	33.66183	35.4859	31.69568	46.56912	48.00221	43.86648	62.66958	77.4162	92.45898	98.99576	102.7051
E	KOR	176.4166	169.0993	173.2685	202.3104	190.1623	188.1906	154.7615	153.4012	139.7617	126.7241	111.2057	102.5857
E	ESP	12.34416	11.46421	10.50945	11.10922	10.34261	12.38466	11.17064	19.77429	20.18678	17.28297	18.9111	17.37248
E	TUR	7.534512	7.01625	6.735017	6.983082	6.589212	5.280601	3.844775	5.079241	6.582262	10.50789	11.67177	11.50554
E	USA	16.27736	20.53276	21.57318	25.48013	27.59643	27.1746	30.25978	30.76766	33.79746	31.59965	28.38744	28.24292
E	URY	25.46	41.57871	51.74149	83.7681	123.2567	129.9465	205.2314	328.2353	322.1002	371.3862	423.1802	374.8388

Table SM2.6 Regression Coefficient from the rolling window regression, calculated in a 10 year window. Results reflect the rate of change of the mean values of factors for each archetype in a given time period.

		1961 - 1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2019
Import dependency ratio	Laggards	-0.00609	0.06426	0.023075	-0.04952	-0.02229	0.049798
	Emergers	-0.05348	0.060016	-0.03404	0.059199	-0.05358	0.016813
	Midfielders	0.014082	0.008604	0.001203	0.008963	0.009507	0.039201
	Grain and Water	-0.00019	-0.00231	0.000703	0.005591	-0.00078	0.005938
	Thrivers	-0.00612	0.022983	0.019032	-0.0051	0.025268	0.020482
GDP per capita	Laggards	11.77976	92.218	17.25657	27.70506	262.5155	70.73546
	Emergers	17.52876	261.5821	109.8302	131.9601	901.6916	275.7355
	Midfielders	121.292	739.3033	425.9551	575.4938	2886.549	540.5532
	Grain and Water	77.88075	284.7422	-45.8615	383.3675	1389.826	-409.885
	Thrivers	287.7736	1393.558	2179.965	1355.899	5482.748	-350.007
Yield	Laggards	0.088875	-0.00866	0.33026	0.1127	0.172009	-0.01382
	Emergers	0.069653	0.159948	0.017881	0.151876	0.496389	0.113437
	Midfielders	0.119667	0.183172	0.253914	0.196533	0.132613	0.091376
	Grain and Water	0.12002	0.223835	0.270705	0.384375	0.351545	0.050297
	Thrivers	0.305506	0.084551	0.249861	0.381599	0.440713	0.230953
Production per capita	Laggards	2.416379	1.691708	-0.41086	-1.10111	12.65318	-5.68323
	Emergers	3.955826	-5.63952	-3.08152	8.759828	28.6139	1.960993
	Midfielders	-3.35104	6.588716	-4.27344	19.82111	6.48482	-7.81689
	Grain and Water	14.44908	48.36039	-31.4984	-20.7825	15.18171	2.434309
	Thrivers	4.970147	3.946415	-0.94002	9.423939	2.79643	-3.24262

Table SM2.7 Country Name and Codes

Country Name	Country Code	Country Name	Country Code
Afghanistan	AFG	Korea, Rep.	KOR
Argentina	ARG	Lao PDR	LAO
Australia	AUS	Liberia	LBR
Bangladesh	BGD	Madagascar	MDG
Benin	BEN	Malawi	MWI
Bhutan	BTN	Malaysia	MYS
Bolivia	BOL	Mali	MLI
Brazil	BRA	Mexico	MEX
Burkina Faso	BFA	Mozambique	MOZ
Cambodia	KHM	Myanmar	MMR
Cameroon	CMR	Nepal	NPL
Chad	TCD	Nicaragua	NIC
Chile	CHL	Nigeria	NGA
China	CHN	Pakistan	PAK
Colombia	COL	Panama	PAN
Congo, Dem. Rep.	COD	Paraguay	PRY
Costa Rica	CRI	Peru	PER
Cote d'Ivoire	CIV	Philippines	PHIL
Cuba	CUB	Portugal	PRT
Dominican Republic	DOM	Romania	ROU
Ecuador	ECU	Senegal	SEN
Egypt	EGY	Sierra Leone	SLE
France	FRA	Spain	ESP
Gambia, The	GMB	Sri Lanka	LKA
Ghana	GHA	Suriname	SUR
Greece	GRC	Tanzania	TZA
Guinea	GIN	Thailand	THA
Guinea-Bissau	GNB	Timor-Leste	TLS
Guyana	GUY	Togo	TGO
Haiti	HTI	Turkiye	TUR
India	IND	Uganda	UGA
Indonesia	IDN	United States	USA
Iran	IRN	Uruguay	URY
Iraq	IRQ	Venezuela, RB	VEN
Italy	ITA	Vietnam	VNM
Japan	JPN		

Supplementary material Chapter 3

Table SM3.1: Guiding questions used in individual telephone interviews with stakeholders

Stakeholder information	1. Name, gender, organisation and the objective of your organisation? 2. a. What is the key focus of your organisation as regards rice? Is it one or 2 of the following – production, research and/or policy? b. What are the main tasks and responsibilities in your current role?
Current system	3. How is the current rice production situation in Nigeria? 4. What factors influence rice production in Nigeria? 5. Is there a relationship between these factors? Positive and negative relationships. 6. What factors are influenced by rice production in Nigeria? 7. Identify 3 drivers that impact the nation's rice production sector? Think bigger scale, national, international, external etc.
Actors	8. Who are the most important actors /stakeholders? 9. Who are the most affected stakeholders?
Trends	10. Do you see certain trends in these factors in the last 10 years?

Table SM3.2: Participating stakeholders' background and involvement in the stakeholder engagement

Stakeholder group	Stakeholder description	Code	Participation in 1st episode of stakeholder engagement	Participation in 2nd episode of stakeholder engagement
Academia	Works in higher education institutions conducting research/teaching in rice and related studies	A-01	yes	yes
		A-02	yes	yes
		A-03	yes	yes
		A-05	yes	yes
		A-06	yes	yes
Research Institute	Works in research institutes related to rice production and offers extension services including IITA, AfricaRICE, Nigerian Cereals Research Institute etc.	R-07	yes	yes
		R-08	yes	yes
		R-09	yes	yes
		R-10	yes	yes
		R-11	yes	yes
		R-12	yes	yes
Farmer	Small scale farmer	F-13	yes	yes
		F-14	yes	yes
		F-15	yes	yes
	Large scale farmer/union heads	F-16	yes	no
		F-17	yes	yes
		F-18	yes	yes
Government agencies/Government departments	At state, federal and West African region levels, working in Nigeria	G-19	yes	yes
		G-20	yes	no
		G-21	yes	yes
		G-22	yes	yes
		G-23	yes	yes
Total no. of participants			23	21

Table SM3.3 – Concepts and Connections originally mentioned by stakeholders, with references to support choice of generalized labels

Terms as used by stakeholders	Generalised label	References
Govt. policies, import bans, foreign exchange, CBN policies, financing policies, depletion of foreign exchange, reduced imports, reduced foreign exchange, smuggling, international trade, Donor agencies, more deliberate attempts/policies made by Government, inconsistent Government policies lead to a poor agricultural system, Self-sufficiency requires a radically committed Government to achieve, policy input, policies that last beyond a government tenure and are enforced, closure of borders reduced competition, border closed at the wrong time – end of production season, good policies-poor implementation	Government. Import restriction policies	Johnson et al. 2013 Okodua 2018 Adesina 2012 Iwuchukwu and Igbokwe 2012 Nasrin et al. 2015
financing and Government support for inputs such as fertilisers, seeds; roads to link to urban buyers and energy to process paddy rice; (fertiliser, seeds, herbicides/insecticides and mechanisation; Private-public development partnerships, expensive inputs with unplanned subsidisation by Government, external donors, international development partners intervention in the value chain, support farmers with irrigation, Government financial and input interventions, Anchor borrowers, financing to farm large fields, inputs in place of cash, out-growers' scheme through CBN	Financing and subsidisation	Johnson et al. 2013 Adesina 2012 Nasrin et al. 2015
Security from herdsmen, conflicts, communal clashes, crisis, migration due to conflict, uncertainty around civil war, conflicts that disrupts farming	Insecurity and conflicts	Alao et al. 2019 Lawal et al. 2018
access to market, connecting farmers to buyers, commercialisation, access to output market, access to market to sell off surplus, poor market and pricing regime, market access, transport to market, increased profit margin with market strategy, eliminating middlemen, no longer subsistence farming, large scale production, up-takers buy up farmers produce	Commercialisation	Johnson et al. 2013 Falola et al. 2014 Awotide et al. 2016 Mgbenka et al. 2015 Nasrin et al. 2015
mechanisation for large scale farming, mechanisation for clearing land, more machines, machinery should be assembled within the country,	Mechanisation	Aboagye et al. 2016 Nasrin et al. 2015 Sims and Kienzle 2016 Van Pham 2016
population dynamics, population growth, new demand for local rice, demand due to urbanisation and changing preferences, imports ban reduced competition by foreign rice	Demand for local rice	Yusuf et al. 2020 Fiamohe et al. 2018 Ajiboye et al. 2019
job creation, youths and civil servants now involved in rice production, galvanised local economy, an influx of people into agriculture as employment, poverty reduction, food security, money used for importation and foreign exchange now remains in the economy, more people can afford to eat rice very often	Local economic growth	Okodua 2018 Abbas et al. 2018 Golub et al. 2019

Local rice is expensive because farmers need to breakeven, foreign rice is cheaper, the consumer is most affected at the end of the value chain, producers take advantage of the import bans, no price regulation, price hiking due to high demand	Market price of local rice	Ayinde et al. 2016 Sadiq et al. 2020
change in consumers preferences, consumer behaviour, campaigns against foreign rice for health reasons, mode of storage; rice is a staple food, local rice no longer just for the rich (ofada rice), people's orientation has changed, consumers prefer white polished rice, urbanisation has increased demand	Consumer preferences	Abdullahi et al. 2019 Ojo et al. 2019 Fiamohe et al. 2019
quality of milled rice sold to consumers; free from odour, long-grain, free of stones and impurities, sometimes it is the same variety as the ‘foreign rice’ but needs to be worked on to meet the standard, Made in Nigeria rice	Quality of local rice	Ajala and Gana 2015
land fragmentation, aggregation of hectares, land tenure policies, availability and suitability of land, lack of land, access to land; change in land use, lands abandoned due to submergence	Landholding	Obayelu et al. 2019 Olarinre et al. 2019
Net returns from the production of rice, lower profit margin, higher profit margin, higher marginal returns, more income, no rice mills so the margin of profit farmers make is low	Economic profitability	Bwala and John 2018 Adjao and Staatz 2016 Ojo and Baiyegunhi 2020
more rice mills, more people in the rice value chain, an influx of people into agriculture as employment, value-added products such as rice flour produced; transporters moving rice from one place to another, more rice-based products	Value chain activities	Osabuohien et al. 2018 Philip et al. 2018 Diakite et al. 2019
more rice mills, cost of destoning machines is high, investment by Government in processing technology ensures high quality of rice	Processing technology	Osabuohien et al. 2018 Ajala and Gana 2015
Costs analysis shows that rice should be sold at #16500, farmers source for everything themselves, high costs of input, Govt should focus on reducing costs of production for farmers, people are on their own, profit margin low, marginal returns of rice supersedes soybean and cassava by 60%, costs of input is high	Production cost	Abbas et al. 2018 Polycarp et al. 2015 Kosemani et al. 2020.
Local rice produced, farmed rice within Nigeria, large millers complained that they do not have enough paddy to mill, a comparative advantage to grow more rice	Rice production	Multiple papers
Adoption of farm technology, improved varieties, conditions for all year round planting, varieties resistant to iron toxicity, improved seed variety, poor yield due to farmers ignorance on seed types, farmer education, high demand for seedlings, farmers realise broadcasting yields lower than seedlings, adoption of new technology, varieties and methods, poor extension services, varieties that can survive 30 days submergence,	Improved farm technology	Yusuf et al. 2019 Awotide et al. 2016 Nasrin et al. 2015 Mgbenka et al. 2015
Irrigation facilities for all year round planting, water management, poor irrigation systems, TRIMMING (transforming irrigation management in Nigeria), irrigation due to erratic rainfall, beyond planting rice close to the rivers, need for boreholes to be dug for farmers	Irrigation facilities	Ajetomobi et al. 2011

Yield/hectare, productivity, higher yield	Agricultural productivity	Ahmed et al. 2017 Sims and Kienzle 2016 Nasrin et al. 2015
Change in land use, farmers switching from cassava and other crops to rice farming, new rice ecologies such as upland are being explored	Rice area	Nasrin et al. 2015 Udondian and Robinson 2018
Government investment in providing fertilisers and pesticides, boosting rice production, increased usage of fertilisers	Fertilisers use	Ojo and Baiyegunhi 2020
Under anoxic soil conditions Fe toxicity is linked to waterlogging, land degradation due to deforestation for farming worsened by floods.	Soil degradation	van Oort et al. 2018 Onyango et al. 2018
Deforestation (conversion of forest to agricultural land)	Deforestation and Biodiversity-loss	
Floods, droughts, change in climate, climate variability, low harvest due to late rainfall, losses due to floods that condemned the rice fields, rainfall and water management, high reliance of rain-fed agriculture, floods discourage investment because floods lead to losses, floods wash off fertilisers, observed change in rainfall pattern, climate change is affecting water availability, desertification, extended rainfall, floods impacts lead to deforestation	Climate impacts	Oguntade et al 2014 Ajetomobi et al. 2011 Ojo and Baiyegunhi 2020
Rice blast, birds, bird control during grain filling, blight, rice pathogens	Pesticides use	Diagne et al. 2013 Singh et al. 2000 Nwalieji and Uzuegbunam 2012 Ojo and Baiyegunhi, 2020
Improved seed varieties that emit less GHG emissions, methane from flooded rice	GHG emissions	Abdullahi and Abdullahi 2020

List SM3.4: Additional comments provided by stakeholders

- Stakeholder R12: Stakeholder Rice value chain in Nigeria is determined by a multi-factorial system including but not limited to landholding, conflicts, limited farming technology and implements, pests and insects, changing rainfall regime and processing technology.
- Stakeholder R9: It will be good if you could share your final findings with the rice value chain actors in Nigeria to guide in precise decision making.
- Stakeholder A5: To a large extent (about 85% by my perceived estimate), activities on rice value chain are driven by the private sector (local farmers and private firms). Again, acceptability of local rice among consumers has improved significantly (about 70% by my perceived estimate) in the last one year.
- Stakeholder R7: I think you may need to include family size as a factor especially for rural communities which produces the bulk of the rice bank. Family size correlates positively with the area under production, which affect rice production and profitability
- Stakeholder R17: Rice production in Nigeria has hydra-headed challenges which have been highlighted in the questions above. The government has a lot to do in making Nigeria self-sufficient in this regard.
- Stakeholder F17: The cultivation of rice is still largely un-mechanised and done by rural farmers. More so, there is a huge influx of small and medium scale rice processors due to current government policies on rice importations. However, the perception of the larger consumer on the quality of local rice is low.
- Stakeholder R11: Rice value chain is an emerging agricultural transformation and innovation in Nigeria. With improved technology, rice production, processing, marketing, profitability and sustainability will be another gold mine in the agricultural sector.
- Stakeholder G22: Rice production in Nigeria is quite in the average level which requires more mechanisation and interest from both the government and private sectors.
- Stakeholder G21: High productivity were obtained under irrigation but the total land area is very low. Improved technology adoption was very low only about 30% and mostly improved seeds. Value chain activities are dominated by middlemen reaping greater benefits than the farmers. Most suitable rice farms are smallholdings cultivated by peasants, increased landholding is mostly by commercial farms who had other interest than farming such as tax relief, reduced import tariff and financial subsidies. Finance and subsidies were largely enjoyed by cronies of politicians rather than the farmers.
- Stakeholder G19: Generally we are yet to achieve a high level of mechanisation in our Rice production. The conflict between herdsmen and farmers is also very high. With the ban on rice importation, farmers are enjoying good prices now.

Supplementary material Chapter 4

Table SM4.1 Connection matrix of the fuzzy cognitive map of Nigeria's rice-agri-food system

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28
C1	1	0	0	0	0	0.8	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C2	0	1	0	0.7	0.7	0	0	0	0	0	0	0	0	0	0.7	-0.8	0	0.7	0.6	0	0	0.7	0	0	0	0	0.8	0
C3	0	0	1	0	0	0	0	0	0	0	0	0	-0.7	0	0	0	0	0	0	0	-0.6	0	0	0	0	0	0	0
C4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0
C5	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.7	0	0	0	0	0	0	0
C6	0	0	0	0	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0
C7	0	0	0	0	0.5	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C9	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C10	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.2	0	0	0	0	0	0	0	0	0	0	0.4
C12	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0
C13	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C14	0	0	0	0	0	0	0.7	0	0	0	-0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C15	0	0	0	0	0	0	0	0	0	0.8	-0.6	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C16	0	0	0	0	0	0	0	0.8	0	0	0	0	-0.7	0	0	0	0	0	0	0	-0.7	0	0	0	0	0	0	0
C17	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0.4
C18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	-0.5	0	0	-0.6	0	-0.5
C19	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.6	0	0	0	0	0	0	0.4
C20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0	0	0	0
C21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0.5	0.4	0	0	0	0
C22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0	0	0	0.5
C23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.8	0	0	0	0	0	0	0	0
C24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
C25	0	0	0	0	0	0	0	0	0	0	0	-0.5	0	0	0	0	0	0	0	-0.6	0	0	0.6	0	1	0.7	0	0
C26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.7	0	0	0	0	0	0	0	0
C27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0.7	0	0
C28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

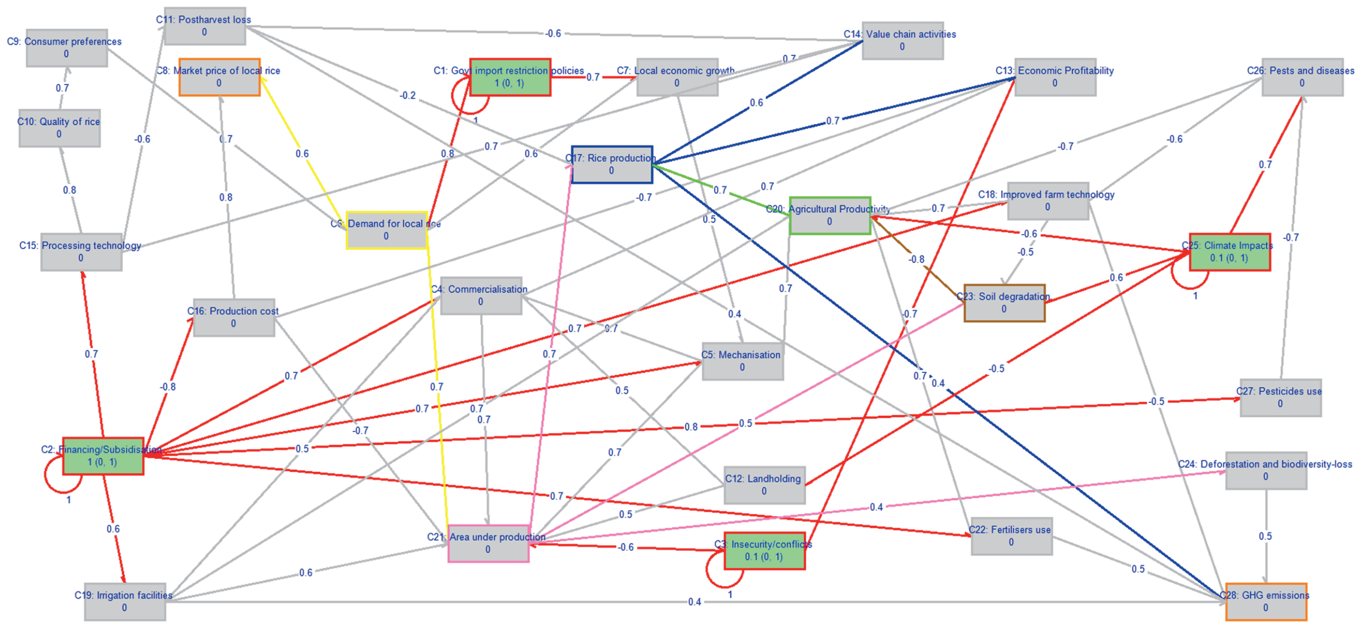
Table SM 4.2 Description of concepts in the fuzzy cognitive map of Nigeria's rice agri-food system

P/S these are the final concepts and connections in the FCM of Nigeria's rice agri-food system. These may differ from previously published versions.

Concept	Description
C1: Govt import restriction policies	Government import restriction policies and measures to reduce import dependency and increase local production.
C2: Financing/Subsidisation	Funds from the Government, donor agencies and private-public development partnerships benefit farmers and other participants in the value chain, e.g. the Anchor Borrowers' programme. Planned subsidization of farm inputs, energy and infrastructure.
C3: Insecurity/conflicts	Herdsmen-farmer conflicts, communal clashes and other internal conflicts causing unrest and losses.
C4: Commercialisation	The farming of rice, not just for family use but for commercial sale; access to markets
C5: Mechanisation	The use of machines and machinery in farm processes
C6: Demand for local rice	Consumers demand locally grown rice as opposed to other alternatives
C7: Local economic growth	Local economic growth that increases the well-being of the local people
C8: Market price of local rice	The current price at which local rice is bought or sold as determined by demand and supply.
C9: Consumer preferences	Consumers' preference for local rice over imported rice and preference for local rice as a staple food
C10: Quality of rice	The physical and physiochemical properties of milled rice
C11: Postharvest loss	Losses after harvest due to milling processes, storage processes etc. leading to quality and quantity degradation.
C12: Landholding	To own or be able to rent land plots suitable for rice cultivation
C13: Economic profitability	Net returns from the production of rice
C14: Value chain activities	Processes of postharvest handling to move rice from an agricultural product to a finished product for consumers
C15: Processing technology	Processing technology in postharvest processes such as threshing, willowing, parboiling, etc.
C16: Production cost	The total cost incurred in the cultivation and production of rice as a food crop
C17: Rice production	The cultivation and production of rice as a food crop
C18: Improved farm technology	Access and adoption of improved technology such as seed varieties and improved management practices that provide technological or genetic improvements in crops.
C19: Irrigation facilities	The availability of irrigation facilities that allow for all-year-round planting, improved water management and the effectiveness of programmes such as transforming irrigation management in Nigeria (TRIMMING)
C20: Agricultural productivity	Overall agricultural productivity is endogenous to production factors such as land, labour and input.
C21: Rice area	Arable land used for rice production
C22: Fertilizers use	Substances, whether natural or synthetic applied to add nutrients to soil or plants to improve plant growth.
C23: Soil degradation	The physical, chemical and biological decline in soil quality leading to a decline in soil fertility and other conditions.
C24: Deforestation and biodiversity-loss	Loss of natural forests and loss of biological diversity associated with agricultural area expansion
C25: Climate Impacts	Changes in the frequency, intensity and variability of climate conditions.
C26: Pests and diseases	Rice pests and diseases such as blasts, birds, blight etc.
C27: Pesticides use	Agro-chemicals for pests and disease control
C28: GHG emissions	Methane and Nitrous oxide emissions from rice cultivation

Figure SM4.3 Fuzzy Cognitive Map of Nigeria's rice-agri-food system

Map from FuzzyDANCES v. 2.0.1.0 (FuzzyDANCES- Dynamic ANalysis of Fuzzy Concepts in Evolving Systems. Developed by Farming Systems Ecology Group - Wageningen University).



Supplementary material Chapter 5

Table SM 5.1a Conversion Rules in iCLUE model

LanduseClass.Water=10,ffff66,Cannot change,100,PercentageDeviation,5

LanduseClass.BuiltUp=20,ffffb3,Hard,100,PercentageDeviation,5

LanduseClass.Rice=30,ffd326,Very easy,1,PercentageDeviation,5

LanduseClass.OtherCrops=40,ff9d26,Very easy,3,PercentageDeviation,5

LanduseClass.NaturalGrassShrub=50,afffef,Very easy,5,AbsoluteDeviation,10000

LanduseClass.OrchardCropTree=60,c1cd9f,Easy,5,PercentageDeviation,5

LanduseClass.Barren=70,ffe7f7,Cannot change,1,AbsoluteDeviation,1000

LanduseClass.EvergreenForest=80,006600,Very easy,100,PercentageDeviation,5

LanduseClass.ConiferousForest=90,006666,Very easy,100,PercentageDeviation,20

LanduseClass.DecideousForest=100,999900,Very easy,100,PercentageDeviation,20

LanduseClass.Plantations=110,002e00,Very easy,15,PercentageDeviation,5

LanduseClass.Mangrove=120,00cc00,Very easy,5,PercentageDeviation,20

Table SM 5.1b Conversion Rules in iCLUE model

	Rice	Orchard	Other crops	Plan-tations	Grass/ Shrub	Man-grove	Built-up	Barren lands	Water	Natural forest
Rice	x		x		x	x	x		x	
Orchard		x			x	x	x			
Other crops			x		x	x	x		x	
Plantations				x	x		x			
Grass/Shrub	x	x	x	x	x		x			
Mangrove	x	x	x	x	x	x	x			
Built-up							x			
Barren lands								x		
Water									x	
Natural forest				x	x		x			x

Water can expand (only in SSP3) to about 80km from current water body; mangroves increase around existing mangroves; maintain area restrictions/protected areas in SSP1,2,5.

Table SM5.2 Profiles of experts consulted

	Expertise and Affiliation
Stakeholder 1	Hydrologist, Ground Water Governance, Center of Water Management and Climate Change at the Institute of Environment and Natural Resources, Vietnam National University in Ho Chi Minh City, Ho Chi Minh City, Vietnam
Stakeholder 2	Water management researcher, Wageningen University
Stakeholder 3	Field Coordinator, International Union for Conservation of Nature (IUCN), promoting lotus cultivation to increase flood retention areas and support livelihoods
Stakeholder 4	Senior Scientist on Sustainable Rice practices such as the AWD at the International Rice Research Institute (IRRI) – Vietnam.
Stakeholder 5	Researcher on rice-based farming systems. Center for Rural Development, An Giang University
Stakeholder 6	Researcher, Can Tho University
Stakeholder 7	Researcher on water management, Institute for Resources and Environment, Vietnam National University Ho Chi Minh, Vietnam
Stakeholder 8	Senior Scientist and Modeller, at the International Rice Research Institute (IRRI) – Vietnam.

Table SM5.3 Derivation of emission intensities for land use classes

IPCC Code	Emissions/Removals source	ha	Total net GHG emissions (ktCO2e)	ktCO2e/ha	Emission intensities (tCO2e/ha)	Reclassified classes as used in iCLUE model
3B1a	forestland remaining forestland	11739092	-42,704.93	-0.00364	-3.64	Stable forest
3B1b	Land converted to forestland	2534786	-11,952.86	-0.00472	-4.72	Land converted to forests
3B2a	Cropland remaining cropland	9748392	-1,026.04	-0.00011	-0.11	Stable cropland and orchards
3B2b	Land converted to cropland	1858060	4,663.64	0.00251	2.51	Land converted to cropland and orchards
3B3a	grassland remaining grassland	420559	0.00	0	0.00	Stable grassland
3B3b	Land converted to grassland	169724	1,383.64	0.008152	8.15	Land converted to grassland
3B4a	wetland remaining wetland	1524752	0.00	0	0.00	Stable water
3B4b	Land converted to wetland	182222	1,046.90	0.005745	5.75	Land converted to water
3B5a	settlements remaining settlements	2518968	0.00	0	0.00	Stable built-up
3B5b	Land converted to settlements	337507	1,919.14	0.005686	5.69	Land converted to built-up
3B6a	otherland remaining otherland	69334	0.00	0	0.00	Stable barren land
3B6b	Land converted to otherland	2019965	7,179.27	0.003554	3.55	Land converted to barren land
3C7	Rice	3958697	49,693.02	0.012553	12.55	
	TOTAL	33123361	10,201.78			

The emission intensity for rice land calculated here is the value used in the Baseline scenario. For other scenarios, the disaggregated emission Intensities based on management practice, location and season are used, calculated in the SECTOR tool. The TOTAL hectares does not include rice area because rice area is already accounted for under cropland but emissions are treated separately under 3C7.

Total baseline emissions are 10,201.78 equivalent to 0.1 mtonCO2e(ktCO2e)

Table SM5.4 SECTOR tool Output, Emission intensities for rice cultivation

The planted area is set at 1 so that the unit is in tCO_2eha^{-1}, the same unit as the emission intensities of other AFOLU land use classes.

Name	Description	Planted area, ha			Practice			Total emission, tCO2e					On-site emission, ton GHG		
								Yearly GHG	GHG intensity	Seasonally GHG emission			Methane (tCH4/season)		
		Season 1	Season 2	Season 3	Season 1	Season 2	Season 3	tCO2e/year	tCO2e/kg paddy	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
1		1	1	-	SRP_north _early	SRP_north _late	NotPlanted	9.27	0.77	3.73	5.54	-	0.13	0.20	-
2		1	1	-	SRP_central _early	SRP_central _late	NotPlanted	8.76	0.73	4.16	4.59	-	0.15	0.16	-
3		1	1	-	SRP_south _early	SRP_south _late	NotPlanted	6.71	0.56	2.38	4.33	-	0.09	0.15	-
4		1	1	-	CP1_north_early	CP1_north_late	NotPlanted	18.94	1.58	7.61	11.33	-	0.27	0.40	-
5		1	1	-	CP1_central_ early	CP1_central_late	NotPlanted	17.89	1.49	8.51	9.38	-	0.30	0.33	-
6		1	1	-	CP1_south_early	CP1_south_late	NotPlanted	13.71	1.14	4.86	8.84	-	0.17	0.32	-

Table SM5.5a SECTOR tool Output overview for Conventional Practice, Central zone, late season

IRRI **Source-selective and Emission-adjusted GHG CalculaTOR for Cropland**

Select a management from the list: CP1_central_late — Save | Load | Del | Reset

Emission factor of fuel	Not considered	0	0	t CO_2e/ha/season	-
Singular N2O emission factor	No adjustment	0	0	kg N_2O/ha/season	-
Pre-season management					
Pre-season water treatment	Non-flooded <= 180 days before season	1	1	N/A	-
Organic amendment	Residue incorporated shortly (<=30 days) before	1	1	N/A	-
Residue incorporation (from previous season)	Not considered (0%)	0	0	t residue/ha/season	-
Within season management					
Diect emission factor of N2O	Not considered	0	0	kg N_2O/kg N fert	-
Indirect emission factor of N2O	Not considered	0	0	kg N_2O/kg N fert	-
Emission factor of fertilizer product	GWP from fert manufacturing	4.77	0	kg CO_2/kg fert	-
Water management	Irrigated - continuously flooded	1	1	N/A	-
Nitrogen fertilizer use	Total amount of nitrogen fertilizer	100	0	kg N/ha/ season	-
End season management					
Residue management	Not considered	0	0	t CO_2e/t straw	-
Weight of burnt straw (Grain:straw=1:1)		4.80	0	t straw /ha/season	-

Table SM5.5b SECTOR tool Output overview for Sustainable rice practice, Central zone, Late season

IRRI **Source-selective and Emission-adjusted GHG CalculaTOR for Cropland**

Select a management from the list: SRP_central _late — Save | Load | Del | Reset

Emission factor of fuel	Not considered	0	0	t CO_2e/ha/season	-
Singular N2O emission factor	No adjustment	0	0	kg N_2O/ha/season	-
Pre-season management					
Pre-season water treatment	Non-flooded > 180 days before season	0.89	0.89	N/A	-
Organic amendment	Residue incorporated long (>30 days) before seas	0.19	0.19	N/A	-
Residue incorporation (from previous season)	Not considered (0%)	0	0	t residue/ha/season	% of grain yield
Within season management					
Diect emission factor of N2O	Not considered	0	0	kg N_2O/kg N fert	-
Indirect emission factor of N2O	Not considered	0	0	kg N_2O/kg N fert	-
Emission factor of fertilizer product	not considered	0	0	kg CO_2/kg fert	-
Water management	Irrigated - multiple aeration	0.55	0.55	N/A	IPCC 2019
Nitrogen fertilizer use	Total amount of nitrogen fertilizer	100	0	kg N/ha/ season	-
End season management					
Residue management	Not considered	0	0	t CO_2e/t straw	-
Weight of burnt straw (Grain:straw=1:1)		4.80	0	t straw /ha/season	Total residue = 20% rice husk + 80% straw

Figure SM5.6 - Results for spatial patterns and emissions for all SSPs including SSP 4 and SSP 5

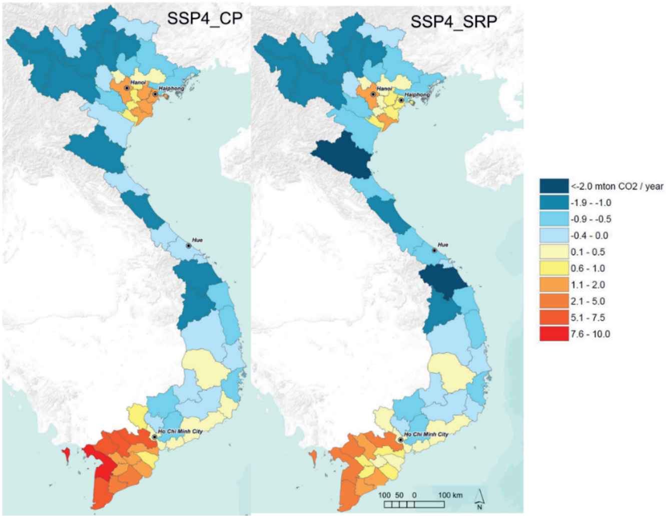


Figure SM5.6a Change in GHG emissions for Vietnam in 2050 under Vietnam's SSP4 Conventional practices (CP) and Sustainable rice practices (SRP)

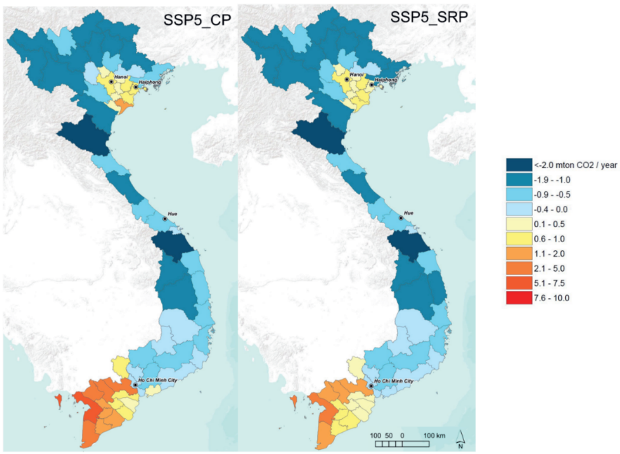


Figure SM5.6b Change in GHG emissions for Vietnam in 2050 under Vietnam's SSP5 Conventional practices (CP) and Sustainable rice practices (SRP)

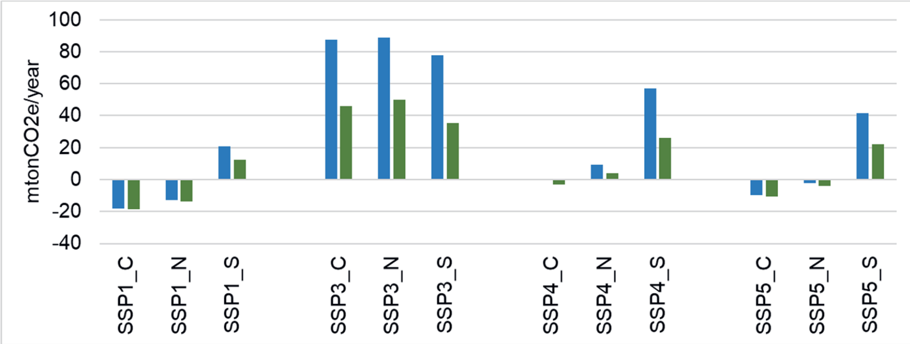


Figure SM5.6c: Total GHG emissions for each scenario by zone (C- central, N-North, S-South) and by and management practice (Sustainable rice recommended practices (SRP) and CP – Conventional practices)

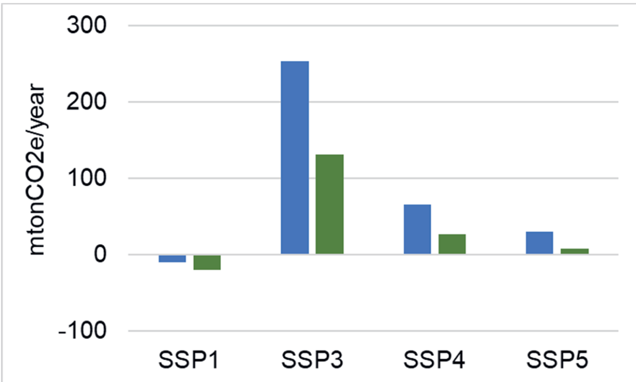


Figure SM5.6d The sum of the change in total GHG emissions in each scenario (including SSP4 and SSP5)

Supplementary material Chapter 6

Table SM6.1 Horizon Scanning Round 1 Survey questionnaire
Welcome!
Please note that this survey is in English and can be completed online with best display on a PC. Some features may be less compatible for use on a mobile device. You have been invited to participate because you have research expertise in any of the broad domains related to rice systems. The survey should take about 20 MINUTES to complete. In this survey, you will be asked how rice systems might evolve by 2050; the challenges and opportunities that will emerge for sustainable rice systems; the areas of research that need to be improved and new/emerging areas of research to prepare for alternative futures. Through this survey, we aim to bridge the gap between researchers, funding agencies and policymakers. By participating you contribute to the results which will shape the narrative of future research and foster collaboration and cross-sectoral knowledge exchange. The survey results would be statistically analysed, used in scientific publication and the results shared with all participants.
We require your personal data (email address) to reach you for a follow-up survey. Other response data will be processed anonymously; that is your responses can not be traced back to you. Our full privacy policy is available here. For more information, please download the survey Introduction document. For questions about the survey, contact [email address].

By clicking the button 'I consent, begin the study' below, you acknowledge that your participation in the study is voluntary, you are above 18 years of age, you consent to the collection of your personal data and that you are aware that you may choose to terminate your participation in the study at any time and for any reason.

o I consent, begin the study
o I do not consent, I do not wish to participate

PERSONAL DATA
Q2 Your email address
____

Q3 Please click to verify.
EXPERT BACKGROUND INFORMATION
Q4 What countries/regions does your research focus on?
You can give multiple answers, if applicable.
____

Q5 How long have you worked in your rice related research domain?

o 0-10 years
o 11-20 years
o 21-30 years
o >30 years

Q6 Which research domain(s) best fits your expertise? (Multiple answers possible)

▢ Agronomy/Crop science/Soil science
▢ Genetics/Breeding
▢ Social-economic/Livelihoods
▢ Policies/Legislation
▢ Environment/Water/Land/Air/Emissions management
▢ Energy/Postharvest/Waste management
▢ Food/Nutrition/Food quality/Food design

Q7 What is your specific expertise and designation? e.g. Lecturer in water management.
____
Q8 What are the three most important CURRENT drivers of change and trends with respect to rice systems?
Think broadly across all social, technological, economic, environmental, or political categories. For each driver, choose the most related driver-category from the drop-down list. Please specify at what spatial scale each driver applies (could be global, a certain region, a certain country, a certain ecology, etc.)

	Specify driver category from drop down list	Write below	Write below

	Social	Technological	Economic	Environmental	Political	Current driving forces of change	Spatial scale of impact
Driver 1	o	o	o	o	o		
Driver 2	o	o	o	o	o		
Driver 3	o	o	o	o	o		

Q9
What are the 3 most important FUTURE drivers of change by 2050 with respect to rice systems?
Think broadly across all social, technological, economic, environmental, or political categories. For each driver, choose the most related driver-category from the drop-down list. Please specify at what spatial scale each driver applies (could be global, a certain region, a certain country, a certain ecology, etc.)

	Specify driver category from drop down list					Write below	Write below
	Social	Technological	Economic	Environmental	Political	Driving forces of change by 2050	Spatial scale of impact
Driver 1	o	o	o	o	o		
Driver 2	o	o	o	o	o		
Driver 3	o	o	o	o	o		

Q10 You have mentioned the following as future drivers of change - ${Q9%232/ChoiceTextEntryValue/1/1}, ${Q9%232/ChoiceTextEntryValue/3/1}, ${Q9%232/ChoiceTextEntryValue/4/1}.
How will these drivers affect rice systems?

Answers can be framed as projections, for example; By 2050, food consumption patterns (future driver) could change to more meats, fruits and vegetables (future change) which will lead to less rice demand (future impact/outcome). You can list multiple projections per driver.

o 1 ________________________________

Q11 The projections which you have made could present challenges to sustainable rice systems. ${Q10/ChoiceGroup/AllChoicesTextEntry} What could these CHALLENGES be?
You can include the how, when, where, whom (affected group of persons). For example; Less rice demand could affect rice farmers (whom affected) in rural Asia (where) through loss of livelihoods (how affected).

o 1 ________________________________

Q12 The projections which you have made could present opportunities to achieve sustainable rice systems.
${Q10/ChoiceGroup/AllChoicesTextEntry} What could these OPPORTUNITIES be?
You can include the how, when, where, whom (affected group of persons). For example; Less rice demand could lead to less rice production (how), reducing greenhouse gas emissions from rice land (where).

o 1 ________________________________

Q13 What research gaps might result from the projected future changes?
____

Q14 What techniques, knowledge and/or methods from your own expertise can you apply to fill these research gaps? ________________________________

Q15 What new research and strategies will be needed to fill the research gaps for a sustainable rice future? ________________________________

Q16 Any additional comments (the next button submits the survey) ________________

Table SM6.2 Horizon Scanning Round 2 Survey questionnaire

Q1 Dear colleague,
Thank you for participating in Round 1 of the Rice future horizon scanning. We received over 100 responses highlighting issues under climate change, consumption changes, farmer demographic changes, technological changes etc.We have organized these as research gaps under blocks. The aim of this second and final round is to prioritize these research gaps on novelty and on relevance to sustainable rice systems. Your response data will be processed anonymously. Our full privacy policy is available here. For more information, please download the survey Introduction document. For questions about the project, contact [email address].
By clicking the button 'I consent, begin the study' below, you acknowledge that your participation in the study is voluntary, you are above 18 years of age and that you are aware that you may choose to terminate your participation in the study at any time and for any reason.
o I consent, begin the survey
o I do not consent, I do not wish to participate
Q2 Your email address ____
Q3 Please click to verify
Please rate the research gaps on relevance to sustainable rice systems and on novelty.

- Novel (means that previous knowledge is limited on this particular subject)
- Not novel (means that sufficient knowledge already exists on this particular subject)
- New to me (if unsure about novelty due to limited knowledge of the particular subject, choose 'new to me')

On relevance, you can choose from high, moderate, or little relevance. You can choose "No idea" if the statement falls outside your scope of knowledge of rice systems. With the comments box, you can make suggestions to improve the clarity and readability of the research gap.
How relevant to sustainable rice systems is this research question/gap? How novel is this research gap? Comments (if any)
high relevance moderate relevance little relevance No idea Novel Not novel New to me

Click to write
RG1.1 Research on the socioeconomic drivers of rice yield gaps across the world
RG1.2 Research on understanding farmers' actual conditions to bridge the profit-loss margin
RG1.3 Research on the development of indicators to assess the actual drivers of change in different rice systems, ex. whether due to climate change and/or human population changes.
RG1.4 Research on understanding the processes of farmers' transformation to sustainable management practices
RG1.5 Research to understand the selection and conservation of traditional varieties by farmers.
RG1.6 Research on emerging land grabs and large scale land acquisitions by wealthy farmers/investors due to rising profitability in rice production
RG1.7 Research to understand different rice market segments to target rice products to specific markets

RG1.8 Research on geospatial analyses of cropland expansion and development of crop-type maps
RG1.9 Research on the replacement of manual, in-person Monitoring- Reporting and Verification (MRV) with remote sensing/satellite technology
RG1.10 Research on shared information systems between key players in the rice value chain for increased transparency in MRV
RG1.11 Research on the monitoring and assessment of the environmental impact of new rice technology
RG2.1 Research on the development and utilisation of genetically modified rice (GMO) and its consequences.
RG2.2 Research on quantifying the effect and responses of rice cultivation at local scale to abiotic stresses/climate change
RG2.3 Research on the potential trade-offs that attempting to limit greenhouse gas emissions from rice production would have on local food security
RG2.4 Research on the shifting dynamics of rice consumption due to increasing incomes and urbanisation in different parts of the world
RG2.5 Research on the impact of urbanisation and industrialisation on availability of arable land for rice production

RG2.6 Research on the effect of increased food insecurity and food prices on farmers practices of sustainable methods
RG2.7 Research on the potential socio-economic impact of technological change to small-scale farmers

RG2.8 Research on the sectoral migration away from farming by youths and by existing farmers
RG2.9 Research on the impacts of increasing rice production on food crop production diversity in Africa
RG2.10 Research on the impact of changing dynamics in global rice markets such as the attainment of self-sufficiency by current rice importers
RG2.11 Research on the interplay and price dynamics between different staple crops develop (ex. wheat/rice prices) at the global scale
RG2.12 Research to develop accurate climate and water information at local scales
RG3.1 Research to develop climate-resilient cultivars/varieties which can thrive under harsh conditions ex. varieties with better avoidance traits and a highly developed root system
RG3.2 Research to develop rice varieties with improved physical qualities (high milling recovery, head rice, length to width ration
RG3.3 Research to develop rice varieties that are efficient in the use of environmental resources (such as solar energy)
RG3.4 Research to develop rice types that are perennial; that is, can be harvested season in and season out.
RG3.5 Research on growing rice on soil-less media
RG3.6 Research on developing floating rice varieties
RG3.7 Research on the development of rice varieties richer in nutritional qualities such as Omega rice, vitamin E rice, high Fe, Zn and low glycaemic content
RG3.8 Research to alter the photosynthesis of rice from C3 to C4 pathway
RG3.9 Research on the development of methanogenic inhibitors for reducing methane emission in rice
RG3.10 Research to optimise increasing CO_2 levels for improved rice crop ecology and productivity
RG4.1 Research on the development of innovative fertilizers for soil fertility management
RG4.2 Research on developing sustainable local seed systems
RG4.3 Research on the integration of rice systems into more diversified, regenerative and nature-based agro-ecosystems to optimize productivity and resource use efficiency
RG4.4 Research on industrial dryland rice production
RG4.5 Research on converting unproductive areas to rice croplands; due to rising scarcity of arable land
RG4.6 Research to develop proactive measures to curtail emerging diseases and pests brought by climate change
RG4.7 Research on fair sustainable business models and supply chains that results in economic benefits to producers and environmental sustainability
RG4.8 Research on carbon farming solutions towards sustainable systems
RG4.9 Research on planetary health diets: healthy diets with minimal environmental footprint
RG4.10 Research to utilise by-products from rice production for other purposes ex. rice straw for the production of biofuels, fertilizers etc.
RG5.1 Research on the use of surface water as a collective regional resource and its potential for balanced supply of rice in the region
RG5.2 Research on upscaling findings from farm-level (micro-level) to regional/global scale (macro-level)

RG5.3 Research on translating science to practice eg. application of genetic advancements
RG5.4 Research on redirecting rice production from export-oriented production to production for local consumption
RG5.5 Research on improving the agricultural literacy of rice producers
RG5.6 Research on the integration of rice systems with tourism
RG5.7 Research to develop diverse food products from rice grains
RG5.8 Research to develop indigenous technology to support the rice value chain
Table SM6.3 Projections made for rice systems in 2050 and interlinkages between seven key issues shown by colour coding

Table SM6.3 Projections made for rice systems in 2050 and interlinkages between seven key issues shown by colour coding

	Climate change	Technological advancements	Urbanisation	Changes in consumer profiles	Changes in labour demographics	Market and Policy shifts	Constraints on natural resources
Hazards such as floods and droughts are stronger and more frequent, leading to crop loss, unstable yields and food insecurity	■						■
Climate impacts (sea level rise, floods etc.) decrease arable land	■						■
Out-migration from areas affected by climate change leads to loss of livelihoods	■				■		
The nutrient composition of rice grains is affected by climate change	■						
Some areas have become more suitable for rice farming	■						■
More sustainable rice production due to climate-friendly policies	■						
Water scarcity compels the adoption of more water-efficient practices	■	■					■
Stress-tolerant varieties as a result of advances in genetic research	■	■					
There is a slow growth rate of emissions from rice production due to technological innovations	■	■					
Technology, automation and mechanisation (use of drones, robots) enable large-scale farming but discourage smallholders		■			■		
Increased mechanisation reduces losses and increases productivity		■					

Technology reduces drudgery fixing the labour shortage problem and enabling women and youth to participate in rice farming							
Technology will enable countries to meet up with rice demand despite climate impacts							
Technology enables farmers to meet consumer demand for high-quality rice							
Shorter duration rice varieties will allow rotation of rice with other crops							
More diverse rice systems, from high-tech monocropping to integrated systems							
Rice systems are more sustainable with lower emissions and more efficient use of water due to technological innovations							
Urbanisation affects the rice consumer profile depending on the region. In Asia, less rice but more meat and vegetables are consumed. In Africa, more rice consumption but lower consumption of roots and tubers							
Cross-regional migration changes consumer profiles in various locations. More people in Europe consume rice, opening up new markets							
Less rice demand affects livelihoods in rice farming communities							
Demand for high quality, more nutritious, low glycaemic rice, organic rice compels producers to focus on quality rather than quantity							
Lower rice consumption per capita as countries become wealthier and more people live in urban areas							
Rural-urban migration leads to inadequate labour in rice farms. Youths prefer white-collar jobs in cities to farm labour							
Urbanisation reduces the agricultural land area							
Cost of labour increases due to an ageing workforce and shortage of labour							
Rural-urban migration of people in search of higher income							
Loss of traditional landraces as farmers emigrate out of their farms							
Youth disengagement from farming triggers a transition to more mechanised farming which increases youth interest in agriculture							
Labour demographic shifts lead to the consolidation of land holdings resulting in larger farms							
Political drivers mainly influence markets more than economic drivers							
A steady increase in global rice demand but a regional shift to Africa, leading to rice area expansion and self-sufficiency policies in Africa							
Self-sufficiency policies distort the global rice market							
Developed countries and multinational companies protect their seed sources, limiting technological innovation in some regions							
Rice farmers transit to fruit-vegetable farming due to higher value							

Political crises trigger fewer investments in rice farming							
Exports continue to drive production							
Increased commodity prices provide opportunities for local rice producers							
Africa launches out as major rice exporter							
Better vertical and horizontal linkages between value chain actors lead to greater efficiency							
Rice loses market share to other crops that require less fertile soils and less water							
Land and water constraints due to population growth, competition from other agricultural uses and climate change							
Water shortages lead to rice price increases and consumers seek other staple food crops							
Adoption of more efficient irrigation systems due to resource constraints							

Current techniques and future techniques proposed by experts as necessary to meet the research gaps

Table SM6.4 Current Techniques

- Conservation rice farming method.
- Using ducks to reduce labour in weeding
- Implementation of Complex Rice Systems at landscape scale
- Quantitative approach on impact evaluation and policy evaluation
- Spatiotemporal analysis of land suitability
- Spatial analysis; Land cover changes and cropland expansions, crop type mapping
- Analyse transition from low-input (dryland) to high-input (wetland) rice systems
- Mapping and characterizing rice growing environments especially lowland / inland valleys Developing Early warning systems and/or decision-support tools
- Characterizing where risks and opportunities are regarding climate change impacts on rice production
- Advance high throughput phenotyping platforms and field-based plant phenotyping tools can potentially answer how rice response changes under a complex environment
- Including expert opinion on rice economics and trade
- Awareness and training.
- Methods for GXE and multiple environments GWAS.
- Regarding the gene discovery, we use several related techniques to identify the actors from smRNAs to proteins
- Behavioural/experimental economics
- Policy formulation and program evaluation
- Better cost-benefit analysis of maintenance work
- Collaboration with private agri-businesses.
- Rent system for storage room for paddy and white rice
- Integration of research in the national politics
- By-product usage in Biogas plants to digest cellulose and hemicellulose in a containerized solution.
- Co-production of knowledge
- Proper calibration of modelling for forecasting.
- Training farmers on how to use technology
- Develop soil amendments which have electron receptors
- Development of rice-based cropping system to diversify rice enterprise
- Identification for mechanisms rice varieties use to cope with the effect of climate change for breeding climate-smart varieties
- Economic (fair sustainable business models and supply chains)
- Ethnobotany
- Understand local farming systems
- Explain motivations of small farmers to government / academia
- Discover links between traditional crops and survival
- Evolution of weed flora and herbicide resistant specie
- Experimental simulation using crop modelling
- Land suitability analyses using ecological niche modelling
- Development, validation and scaling of climate-smart agriculture technologies and climate information services
- Capacity building of stakeholders at national and local levels.
- Field phenotyping of rice, novel genes discovery to improve rice resilience to adverse conditions.
- Pest/disease monitoring based on mobile phone app.
- Development of abiotic stress tolerant varieties using genomic assisted tools
- Extension activities for transfer of technology. Such as farmers training, exposure, visits, surveys, field demonstrations etc.
- Further refinement of the Sustainable Rice Platform (SRP) Standard and its assurance scheme.
- Stakeholder engagement along the value chain to ensure adoption of climate smart rice varieties

- Good production and post-harvest techniques
- Social surveys to answer questions such as “How do new varieties respond to the environmental conditions in farmers' fields to better understand why farmers do or do not continue growing a new variety.”
- Improving resource use efficiencies
- Influencing policy decisions for betterment of rice production
- Rice-fish system
- Nitrogen application techniques
- Innovative climate finance and business models
- Investment in agricultural research and development
- Biotechnological methods and tools
- Machine learning, big data applications including GIS and satellite data
- Digital methods and tools
- Agrifood value chains
- Testing and dissemination of modern technologies at local level
- Knowledge in analysing and quantifying the GHG emissions produced.
- Controlled environment farming such as is being embraced by the horticulture industry
- Knowledge/expertise on weed and parasitic weed ecology and management.
- Knowledge/expertise on developing more water-use efficient and nutrient-efficient cropping systems (mainly in Africa).
- Near-real-time crop simulations and monitoring
- Yield simulations and estimations
- Making small and family rice farming climate and technology smart: collective impact approach
- Market sorting experiments to reveal consumer preferred grain quality traits across Africa
- Screening of existing germplasm for Glycaemic index, grain Protein Fe, Zn and phytate
- Support the piloting and scaling of climate resilient, environmentally friendly and gender responsive technologies in Africa through different technology delivery infrastructures
- Multi-stakeholder Innovation platforms, Consortium of rice seeds enterprises and millers, Integrated Youths in Agribusiness hubs and Individual private companies.
- Multidisciplinary approach
- Modelling and participative research
- Multi-level perspective analysis
- Game theory applied in land-use planning
- Understanding processes of technological change (often known as 'innovation')
- Land levelling techniques
- System design
- Participatory research among the key players in rice value chain
- Policy analysis methods and impact assessment tools
- Polycultures and complex rice systems
- Permaculture
- Water harvesting
- Sustainable local seed systems
- Practical demonstration of prospects in rice agronomy and processing
- research on how trait variation is partitioned across genetic groups could enable greater understanding of which combinations are beneficial in future conditions
- Policy research
- Engineering for designing and manufacturing low-cost machines for direct seeding
- Capacity building
- Competitive funding opportunities for rice research and education of the next-generation rice farmers and professionals
- Investment in digitalisation of the rice value chain (low-cost digitalisation and open-source knowledge)"
- Alternate wetting and drying
- Slow-release N fertilizer
- Rice modelling

- Rice-vegetable systems and farming systems.
- Scaling up new rice technologies - example of Smart-Valleys technology
- Demand-driven technologies, rather than the most advanced or one-size-fit-all ones, are critical for the rapid adoption
- Stakeholder engagement methods to study stakeholder perceptions and develop robust solutions
- Input optimisation analysis
- Appropriate mechanisation
- Training in the fabrication of prototype equipment for land and post-harvest operations
- Promote collaboration between stakeholders in production, market, policy maker, manager, scientist
- Use of weed science to manage weeds with different control methods, like crop rotation, physical methods and chemical methods.
- Value chain mapping; analysing cropping systems rather than individual crops; understanding limitations of top-down technology transfer due to demographic, infrastructural, socioeconomic and agroclimatic circumstances
- Water accounting. This will help provide a spatially explicit account of water available, how much is used for specific sector and how much remains for further allocation.
- High-level policy dialogues

Table SM6.4 Techniques needed in the future

- Better data on areas cultivated with rice (distinguish between dryland and wetland)
- Crop simulation models of rice yields under different management conditions
- Couple data on historic and projected climate change with hydrological models to analyse water consumption
- Capturing the heterogeneity (in biophysical, environmental, social, economic, policy domains) in the current research in the key to be better prepared for the projected changes "
- Rice yield improvement on rice conservation farming systems
- Potential exchanges between duck and rice farmers
- Development of method to landscape approaches for those sustainable rice farming"
- small farmer friendly climate smart technology development
- fast-tracking urban demand and supply of quality rice
- small farmer friendly policies development
- regional cooperation for equitable use of water resources
- Adequate engagement of farmers, processors, policy makers and users in the research agenda
- More socio-economic research in rice systems to recommend optimum investments in rice businesses
- Machine learning can play a pivotal role
- Work more with the private sector
- Build the capacity of the next generation of agricultural scientists, extension workers, policymakers and leaders in the food systems
- Engage with governments on policy and multi-sectoral partnerships on achieving SDGs
- Artificial intelligence
- Connectivity in rural areas
- Low-cost mechanisation and digitalisation throughout the rice value chain
- Water-saving and smarter use of water for irrigation (policies, technologies, capacity building)
- Cooperation: Funding opportunities shall prioritize access to global or regional partnerships
- Public-private partnerships
- Breeding and science aspect, we need to study Africa such as weather, soil, culture.
- Circular agronomy
- Farming as business
- Improved resource use efficiencies
- Precision Agriculture
- Collaboration and training of farmers, experts and decision makers will be key.
- Collaboration between scientists coming from different areas and sectors to connect different parts of the whole system together and find out the real driving factors.

- Cross-system research, i.e. rice-shrimp, rice-upland crop, etc.
- Develop green rice which can produce less CH4 emission and higher productivity
- Develop functional soil amendments and fertilizers which can suppress methane flux in rice paddy
- Developing sustainable intensification methods for smallholder farmers in Africa (e.g. , including alternate wetting and drying combined with adapted varieties. integrated pest/weed management options under changing climates, purposeful integration of trees in rice production systems, increasing crop diversity).
- Development of floating and perennial rice that sustainability harvested
- Digital agriculture
- Efficient suitable rice variety breeding for each ecology and local conditions.
- Detailed mapping of suitable locally rice production areas according to each main rice agroecology (irrigated lowland, rainfed lowland, mangrove, highland)."
- Engagement with stakeholders and policy makers
- Translating available research evidence into actionable policy instrument to make changes"
- Focus on the economical parts of scaling.
- Systemic approach
- Mapping
- Multidisciplinary studies
- Herbicides residues effect, the importance of micro nutrients for rice and post-technology will be needed to fill the research gaps for a sustainable rice future.
- high throughput phenotyping, genetic composition modification from discovery of novel genes to rice resilience to adverse climatic conditions. Socio-economic research on impacts on rice farmers on less rice production.
- High vitamin, Omega 3 rice breeding
- 15N isotope technical
- 13 Carbon technical
- Transdisciplinary research approach(research has a very practical, actionable orientation, engaged with communities and their knowledge and practices and situations.
- Most methods and tools are available, but underutilized.
- Identification of climate-smart varieties on regional basis
- Identification of compatible crops in rice-based cropping system "
- Improved varieties; disease resistant varieties, manufacture of modified equipment for cultivation, processing and marketing
- Going back to the basics, without critical core expertise in many areas of science such as soil science, crop nutrition, crop health, agronomy or crop physiology. Without these basics, it is not possible to tackle bigger challenges in a multi- and transdisciplinary manner.
- Interdisciplinary (not just beta-gamma, but alpha-beta-gamma),
- Multi-actor research approaches
- Increased and sustainable investment in agricultural R&D from governments
- Public-private partnership
- Finding an equilibrium between fundamental, applied research and development initiative
- Innovative thinking by looking at solutions that have been successful in other sectors (energy, health, transportation, etc.) and adapting the approach to agriculture.
- Large scale behaviour change is necessary which will also require adapting successful approaches to behaviour change from other sectors, such as health and education.
- Rapid and inclusive technology development and iterative testing and design processes with users that allow for quick research and development cycles and value failures as learning opportunities.
- It will be crucial to ensure stable, long-term funding for basic rice science research
- "It will be need based research which will vary as per regional, local needs
- Researchers can focus their research on more applied aspect towards product development and delivery and creation of more impactful scientific manuscripts whose recommendation will be more adaptable, repeatable and stainable across the globe."
- Long term vision in planning

- Multifunctional agriculture
- Agro-ecological rice systems
- Market research for sustainably cultivated rice and of rice free of residues.
- Nature-based solutions
- Less dependence on business interest of multinationals
- Reducing the fragility of smallholder farmer systems
- Most of the sustainable rice work is targeted towards plot level, seasons and individual levels. The interaction of various production system factors as well as value chain segments is poorly understood.
- Sustainability needs to be assessed at a system-level and at scale.
- Multi-disciplinary collaborative research
- Policy support and implementation that support domestic rice production and sector development in SSA countries.
- Strategy to conserve agro-diversity in situ (on farms) not only in germplasm banks
- Research needs to be translated into actual solutions. Most of research and strategies on rice/agriculture production are available, but the implementation/operation is very limited. Remote sensing is a good example. While many research groups have been focusing on the topics for years, barely any solutions are in use today.
- Research on policy aspect and technologies
- Research on water-rice production and flow dynamics of the Mekong River
- Technologies in rice root biology and growth in soilless media
- Scientific and Indigenous knowledge integration
- Space applications
- Advance remote sensing applications
- Automated crop monitoring
- Strong collaboration with the physical and social science groups.
- Strong policies that focus on regional programs, rather than national policies in Africa.
- Sustainable and inclusive scaling mechanisms to ensure the adoption of technologies.
- Crop insurance
- Sustainable financing mechanisms
- Technology-based agronomy to be more resource and input efficient.
- Generate long term data to fill models to evaluate possible production trends, pros and cons.
- The research objective is based on the specific requires of each local condition and shortening the procedure and period of field testing.
- Understanding incentives. Farmers need more incentives to a) choose farming as a career, b) implement environmentally-friendly management practices and c) adopt new varieties. This understanding of incentives should feedback to those developing new technologies (breeders, agronomists).
- Upland rice production, improve variety to reduce water use and improve yield.
- Expertise knowledge and environmental experience need to work together.
- land use plan should be implemented accordingly and allocation of water resources should be managed to avoid water loss
- Improve rainwater harvesting and utilisation for Agricultural production
- Improve irrigation infrastructure and water storage facility
- Reduction of production cost in agriculture production and improve commercial rice production
- Use of biotechnological methods
- Digital methods and tools
- Viewing rice not just as a commodity but part of a cropping system and ecosystem.
- Multi-stakeholder engagement-- involving various stakeholders to shape research agendas.
- Water management that will allow diversification in the rice-based system.
- Biodiversity management that will improve ecosystem services in rice-based systems.
- How can technology be adopted by smallholder farmers in more efficient way."
- Integrated water management might still be valuable.

Summary

Agricultural and food systems must increase production while preserving natural capital to ensure food security and sustainability. This grand challenge of sustainable agricultural production is also stressed in the UNFCCC's Paris Agreement. Food production should not be compromised while working towards climate change adaptation, mitigation of greenhouse gas (GHG) emissions and resilience. This challenge presents tensions between its objectives due to these systems' complex nested and dynamic nature, inherent heterogeneity and multiple interacting dimensions and scales. A comprehensive integrative analysis of these complexities, interactions and interdependencies is necessary to attain sustainable systems. In my thesis, I contribute to this need for integration through a systems-thinking approach, focusing on rice sustainability through the following research questions (RQs):

RQ1: What national-level variations in key characteristics have shaped the historical and present sustainability of rice systems?

RQ2: What is the current structure, functioning and related dynamic behaviour of rice systems?

RQ3: What are the implications of future social, economic, environmental and institutional changes on the sustainability of rice systems?

RQ4: What pathways and strategies need to be established to ensure the sustainable development of rice systems?

These RQs each focused on a rice sub-system, were addressed in Chapters 2 to 6. In Chapter 7, a synthesis of the research results from each chapter follows.

Chapter 1 introduces and conceptualises the grand challenge of sustainable agriculture and presents a systems thinking approach implemented throughout the other chapters. The resulting conceptual framework applies two techniques: Archetype analysis to study past-to-present rice systems and scenario planning to explore future rice systems. Each technique uses specific methods to answer an RQ in each chapter.

Chapter 2 classifies 71 countries into archetypes based on their resilience to rice-price spikes as a function of their short-term and long-term capacities and vulnerabilities. Five archetypes are identified with different combinations of factors which make them more

or less resilient. These are the ‘Laggards’, the ‘Emergers’, the ‘Midfielders’, the ‘Grain and Water’ and the ‘Thrivers’.

Chapters 3 and 4 link to Chapter 2's worldwide archetype analysis by comprehensively studying Nigeria’s rice system within the Emergers archetype. A Fuzzy Cognitive Map is co-produced with stakeholders to describe Nigeria's current rice system and identify unsustainable patterns. Effective systemic government policies are one strategy among others proposed to advance Nigeria's rice sustainably.

Chapter 5 studies Vietnam’s rice system of the ‘Midfielders’ archetype (from Chapter 2) to spatially quantify future land use GHG emissions. This study uses two user-friendly models - the Conversion of Land-use and its Effects (iCLUE) model that spatially allocates land and the Source-selective and Emission-adjusted GHG CalculaTOR for cropland (SECTOR) model to estimate GHG-emission intensities by location, season and rice management practices. The study demonstrates the importance of sustainable practices and of using spatial estimates in GHG inventories.

Chapter 6 reports a horizon scanning activity with international rice experts. The experts identify the 25 most important research gaps to be prioritised to achieve sustainable rice systems by 2050. The research gaps are presented under four themes: 'Sustainability Interactions'; 'Agricultural Development'; 'Genetics, Breeding and Crop Physiology'; and 'Governance and Policies'.

In Chapter 7 I reflect on the methods used in my thesis and demonstrate how combining and integrating the methods improved the research on rice systems. I further synthesise my research findings from each chapter and visualise these findings in a system map. This system map presents key factors and their relationships leading to interaction, interdependencies and emergent system properties that contribute to (un)sustainability in rice systems. This map depicts possible pathways to sustainable rice systems.

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To my glory and the lifter up of my head
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In the weak and the strong, where we all belong
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A blooming, independent scientist!

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About the author

Glory was born on 15 July 1989 and raised in the coastal city of Calabar, Nigeria. An intrinsic interest in nature and the environment led her to take the biological science route at Federal Government Girls' College, Calabar. After that, she began her study of Agriculture at the University of Benin in 2006, where she specialised in Fisheries, followed by an MSc in Aquatic Pathobiology at the University of Stirling, United Kingdom in 2014/15.

Her interests evolved into climate change and broader societal issues, so she joined the MSc programme in Climate change, Development and Policy at the University of Sussex, UK in 2016/17, concluding with an MSc thesis on the usability of seasonal climate forecasts to farmers.

In 2019, she began a PhD at Wageningen University in the Netherlands with rice as the main subject. Her main motivation was to uncover the underlying drivers linked to rice food security and how these might change in the future. During her PhD, in 2020, Glory won the Climate, Food and Farming, Global Research Alliance Development Scholarships (CLIFF-GRADS) under the CGIAR Research Program. Glory also received the Green Talents Award - an International Forum for High Potentials in Sustainable Development to promote the international exchange of innovative green ideas within the field of sustainability.

In addition to research, Glory mentors youths, such as in the Youth Food Lab of WUR, on food security and sustainable development issues. Glory is also an academic and life skills facilitator. After her PhD, she continued as a postdoctoral researcher in the Environmental Systems Analysis Group of Wageningen University. She looks forward to applying her systems thinking skills in new horizons towards sustainable development.

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K O N I N K L I J K E N E D E R L A N D S E
A K A D E M I E V A N W E T E N S C H A P P E N

The SENSE Research School declares that **Glory I. Edwards** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 43.0 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2019)
- Research in context activity: Organising a horizon scanning activity involving international rice researchers (2022)

Other PhD and Advanced MSc Courses

- Agent based modelling with NetLogo, Georg-August-Universität, Göttingen (2019)
- Summer school on transdisciplinary research, IRI THESys, Humboldt University, Berlin, Germany (2019)
- Managing risk in the face of climate change, WCDI/ADPC, Thailand (2019)

External training at a foreign research institute

- Research stay, Humboldt University, Berlin, Germany (2022)

Management and Didactic Skills Training

- Tutor at MSc course - Engaging and Modelling with Stakeholders (2022)
- Tutor at MSc course - Adaptation and Mitigation Services for Society (2022)
- Supervising Masters course – Regional Environmental Management (2023)
- Speaker/Key resource person at the International Postgraduate Course on Land Dynamics organised by the graduate schools WIMEK/PE&RC at Wageningen University and the University of the Free State, South Africa (2023)

Oral Presentations

- *Achieving sustainability in rice systems across spatio-temporal scales: a horizon scanning activity.* WIMEK symposium on transdisciplinary research 29 September 2022 Wageningen, The Netherlands
- *The Greenhouse Gas (GHG) emission potential of Sustainable Rice Platform (SRP) practices for sustainable rice cultivation.* 2020 CLIFF-GRADS Science Collaboration Series 7-28 October 2022

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

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