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Land Use, Livelihood, and Legislation: An Agent-based Model to Investigate the Impact of a Policy Regime Switch on the Vietnamese Mekong Delta in the Context of Climate Change

Supervisor:
Professor Andrea TEGLIO

Graduant:
Bich Thu HOANG
Matriculation Number: 875517

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Abstract

The Vietnamese Mekong Delta (VMD), known as the “rice bowl” of Vietnam and one of the world’s leading producers and exporters of agricultural products, is under threat from climate change. However, the current agricultural policies of the region are rife with clashing objectives and incompatible interventions, which make them generally ill-equipped to confront the challenges that climate change poses. This regretful inefficacy is in part the result of inadequate policy assessment methodologies that fail to capture the interconnected relationships between the human and the environmental systems, as well as the resultant consequences. To help address this knowledge gap and facilitate policy formulation, we propose an agent-based model (ABM) that, (i) integrates the human and the environmental systems, (ii) can account for complexity and unintended consequences, and (iii) is modular and flexible. The model is used to investigate the impact of a policy regime switch in the context of climate change. Specifically, the model considers how a switch away from the non-structural measures of the rice-first agenda would affect land-use choices of farmers in the Soc Trang Province while taking heed of the worsening saltwater intrusion. The results suggest that, while not every measure is of equal potency, renouncing fully the rice-first agenda would have a negative impact on food security and the environment of the region in the face of severe saltwater intrusion.

To Mum and Dad, who taught me the value of rice.

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I would also like to thank my friends, who never let me put myself down. They know me too well, and stand by me even when I'm at my most contrary.

The loudest cheer goes to Daniel and Justin, who proof-read this thesis the night before submission. They say it's timezones; I say it's friendship.

And finally, I would like to express my sincerest gratitude to my Mum and Dad, who let me get away with everything, even this thesis.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

In the spring of 2020, as the world found itself breathless in the fight against the COVID-19 pandemic, the people of the Vietnamese Mekong Delta (VMD) had another problem at hand. Due to a combination of climate change effects and intensive economic activities in the region, saltwater was intruding earlier, deeper, and for a longer period of time than ever before, desiccating a vast swath of rice paddies and threatening the income of millions of people (Ministry of Agriculture and Rural Development (MARD), 2020). The damage caused by this event was expected to be more severe than that caused by the great drought of 2016, which already cost the region approximately 400 million USD and pushed many rice farmers out of their lifelong livelihoods.

With two big issues happening simultaneously, the Vietnamese government intervened. An export ban on rice was imposed for the purpose of safeguarding the country's food security during the pandemic (A. Tu, Minh, & Chau, 2020), leaving rice to spoil in ports at the same time as farmers wrestled with the aftermath of the severe saltwater intrusion out in the fields (N. C. Mai, 2020). This prompted experts to voice their concerns regarding the risk of a rice crisis on the same scale as the one in 2008, as well as concerns for rice farmers, who were to bear the brunt of the ban (Thi, 2020). At the time of writing, there are no official reports or statistics that assess the impact of either the severe saltwater intrusion or the export ban.

This situation is nothing new. The VMD has for a long time been witness to many questionable policies—policies that are substantiated only by surface understanding and limited data. The region after all is at the centre of a complex web of human and environmental activities, whose effects on the VMD and the people are difficult to grasp due to the sheer quantity of variables, and, in turn, the high degree of uncertainty involved. Attempts to take apart this web and study it in detail have achieved only moderate success, which leaves a gap in the knowledge base meant to facilitate discussions and inform good policy decisions. Combined with a weak institutional structure, this exposes the VMD to external threats, both human and environmental, without the safety net of effective policy interventions.

The low efficacy in analyses and assessments regarding the impact of natural processes, human activities, and policy interventions in the VMD boils down to the shortcomings of routinely used methodologies. Qualitative methods are incredibly useful in uncovering hidden dynamics but greatly restricted in scale and lacking in the persuasiveness that funds projects and convinces policymakers. The quantitative methodology of choice—cost-benefit analysis based on partial and general equilibrium models—is evidently not designed to handle systems with high complexity. Its low competency in admitting and managing heterogeneity separates it from the real world where variety prevails. Its lean towards linearity and determinism makes it unable to explain non-linear, unexpected interactions and their consequences. Its lack of an explicit spatial representation restricts its usefulness in analysing any systems that are heavily dependent on their physical surroundings, such as agricultural economies.

Naturally, researchers have not been idle. Many methodologies have been borrowed and developed to strengthen their analytical capacity and aid policy formulation in the region. Among the more common of the new tools, agent-based modelling (ABM[1]) attracts our attention the most. ABM has complexity theory as its foundation, a bottom-up philosophy as its modus operandi, and fully customisable agents as its building blocks. This allows ABMs to reconstruct any systems, complex or otherwise, and study them in depth. ABM appears singularly capable of fulfilling our objectives.

1.1 Thesis objectives

The VMD is in need of a policy impact assessment method that can capture the complex relationships between the human and the environmental systems, explore hypotheses as well as possibilities, and provide timely analysis regarding the dynamics amongst present factors.The broad objective of this thesis is therefore to explore the potential of ABM as one such tool.

To do so, we aim to develop an ABM of the economic landscape of the Soc Trang Province in the VMD, integrating the human and the environmental systems, with a focus on saltwater intrusion. The model should be able to generate general but empirically verified land-use patterns that reflect the livelihood options of farm agents. Afterwards, the model is used to explore how a set of “rice-first” measures—policy interventions that promote the cultivation and production of rice—affect the local environment, the economic interest of farmers, and food security in the region, taking into account severe saltwater intrusion events similar to the ones in 2016 and 2020. This way, we expect to assess the impact of a switch away from this “rice-first” agenda on the VMD in the context of climate change.

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[1] We follow the literature and abbreviate “agent-based modelling” as ABM and “agent based models” as either ABMs or ABM with an article appended.

1.2 Thesis outline

The thesis is structured as follows. Chapter 2 elaborates on the need for an integrated policy impact assessment methodology by presenting an overview of the VMD, the role of agriculture in the region, the climate change challenges it is facing, as well as the lack of success on the government side in formulating a comprehensive development and adaptation plan for the region. Chapter 3 reviews the new generation of assessment methodologies and argues, on the basis of its strengths and weaknesses, that ABM is the one most suitable to our needs. Chapter 4 introduces our formal research question and the model in significant detail. Chapter 5 presents and discusses the results obtained from the model, along with its limitations and recommendations for further study. Finally, Chapter 6 concludes.

Chapter 2

Land use, livelihood, and legislation in the Vietnamese Mekong Delta

2.1 Introduction

Agriculture is a valuable driver of economic development in Vietnam, accounting for 13.96% of GDP and 3.07% of exports as well as employing 34.5% of the total labour force in 2019, more than any other sector (General Statistics Office of Vietnam (GSO), 2020). Rice, shrimp, and catfish are some of the country's leading agricultural products. As of 2020, Vietnam is the third-largest rice and farmed shrimp exporter, and the biggest catfish exporter in the world (Knoema, 2020; Seafood Watch, 2020; Vietnam Association of Seafood Exporters and Producers, 2021).

Among all the agricultural regions in Vietnam, the VMD has a significant role: it has consistently contributed more than 50% of the country's rice production, 80-90% of rice exports, 80% of shrimp production, and 60-65% of shrimp exports (Communist Party of Vietnam Online Newspaper, 2019; Kien, Han, & Cramb, 2020; P. Q. Le, 2019; Pongthanapanich, Nguyen, & Jolly, 2019; World Widelife Fund for Nature, 2017).

The VMD is also under grave threat from climate change. As a low-lying area situated in a zone prone to tropical cyclones, the VMD is susceptible to sea level rise and its related issues such as flooding, erosion, and saltwater intrusion, to extreme climate events like drought and severe storm surges, and to changes in weather patterns that could upend the lives of millions of people living there. Numerous studies of the impacts of climate change on the VMD have predicted yield and economic losses that would threaten the economy and food security of Vietnam and beyond.

Despite the importance of the VMD and its agricultural sector as well as the gravity of the climate change challenges, mitigation and adaptation policies in Vietnam are still wanting. There are two main causes: first, as acknowledged in Resolution 120/NQ-CP (Government of Vietnam (GVN), 2017) by the government themselves, there is a lack of coordination and synchronisation between different state administration levels, regions, sectors, and industries. Second, there is a knowledge gap of how policies formulated nationally would impact the practices and performances locally (Q. H. Nguyen et al., 2020). Existing policy assessment methods employ top-down approaches and focus primarily on ex-ante, short-term results to generate proof of impact rather than to achieve understanding of the causal processes and feedback mechanisms at the systemic level (H. N. Nguyen, Fliert, & Nicetic, 2015). These are arguably the two biggest barriers in the development of effective adaptation plans both nation-wide and in the VMD.

Given the situation, in this chapter we argue in favour of an impact assessment method that can be implemented ex-ante, take a long-term, inter-sectoral view, allows for the dynamics on the ground, and encourages cooperation. To do so, we first provide an overview of the VMD, the agricultural sector in the VMD, and current climate challenges. Then we argue that the two problems of policy planning in Vietnam as outlined above have given rise to policies with unintended consequences, which, at best, complicates the already complex situation at hand and, at worst, sets back mitigation and adaptation endeavours in a region that urgently needs them.

2.2 The Vietnamese Mekong Delta: an overview

2.2.1 Geography

The VMD is located in southwestern Vietnam and divided into 13 provinces. It accounts for 12.3% of total land area (about 40,640.7 km^2) but 54% of the country's total rice land and is responsible for almost 56% of its total rice production in 2019 (GSO, 2020). Such high agricultural productivity is due partly to the region's favourable geographical and physical characteristics. As a mixed tide- and wave-dominated river delta (Tamura et al., 2012), the VMD was built up by the fluvial processes of the Mekong River where it splits into two main distributaries (Tien and Hau Rivers) and nine channels before pouring into the East Sea (internationally known as the South China Sea). The area has what is considered to be one of the lowest elevated plains in the world: new elevation data and models suggest that on average the VMD lies only 0.82 m above local sea level (P. S. J. Minderhoud, Coumou, Erkens, Middelkoop, & Stouthamer, 2019).

The VMD has tropical climate with the influence of the Asian monsoons. The mean temperatures and humidity are consistently high throughout the year. There are two seasons: a dry season that lasts from December to April with little rainfall, and a rainy season that lasts from May to November, with the southwest winds bringing heavy rains (Ministry of Agriculture and Rural Development, 2016).

Along with a network of natural distributaries, the region has numerous man-made channels, canals, and dikes constructed to convert wetlands into agricultural land. This complex system ensures that the VMD has a highly dynamic hydrological regime. The levels of river flows in the region vary considerably: extremely high during the rainy season and low during the dry season. This, together with the low topography, makes salinisation and flooding unavoidable seasonal features of the delta (Toan, 2014).

Salinisation, defined as the accumulation of salt that has dissolved in water in the soil at levels detrimental to crops and aquatic lives, occurs during the dry season. It is a slow onset phenomenon that also varies in duration and intensity depending on numerous factors (Tran Anh, Hoang, Bui, & Rutschmann, 2018). Considerable uncertainty in these factors makes it difficult to forecast salinity level with high accuracy. The complex system of canals also allows saltwater to intrude further. The southern and eastern coastal and intertidal areas of the VMD are most affected by salinisation, with a large area of land reaching a saline concentration of around 6 dm/S ($\approx$ 4 g/l), an intolerable level for many varieties of rice (Toan, 2014). Saltwater intrusion does not only damage crops but also affects freshwater sources that supply water for domestic use and is a big cause of concern in the region.

Around half of the VMD is flooded every year (Deutsches Zentrum für Luftund Raumfahrt, 2018). Flooding occurs from June-July to November-December and is the result of three factors: the floodwater carried by the Mekong River from Kratie (Cambodia), the intense rainfall over a short period of time which provides fresh floodwaters, and the tides of the East Sea and the Gulf of Thailand which bring seawaters to the estuaries (Hung et al., 2012). As these factors vary from year to year, annual flooding can last from a few weeks to months. The natural lake system in Cambodia and large floodplains in the VMD act as reserves that regulate flooding. Flooding levels tend to reach their peak in around October then slowly recede (Wassmann et al., 2019).

Annual flooding is deemed a necessary evil in the VMD. While annual flooding has incurred big economic and human losses (UNDP, 2003), it is also the key to the highly productive soils in the VMD. The fresh floodwaters from upstream is the main transporter of nutrient-rich sediments to the delta, replenishing not only the fertility of rice paddies but also wild fish for aquaculture. Under normal flood conditions, more than half of the nutrients necessary for crops are provided by sediment fluxes. Freshwater flooding also reduces salinity and keeps the saline boundary at the coast, flushes out toxin and agrochemicals, and provides breeding sites for fisheries. The areas most susceptible to annual flooding are the north, the west, and the centre (Wassmann et al., 2019).

2.2.2 Population

The VMD is home to around 17.2 million people (18% of the country's total population), of which 74.8% live in rural areas. The region's population growth is slowing down, due to out-migration rate outpacing natural increase rate (GSO, 2020). 8.11% of the population are of ethnic minorities (T. S. Nguyen & Nguyen, 2020).

In 2019, 86.7% of the VMD labour force had no formal qualification, the highest rate in the country. The region also had the highest unemployment rate[1] and the highest under-employment rate (2.90% and 2.41% respectively). While there has been a drop in the under-employment rate in the past few years, the unemployment rate has been constant (Figure 2.1).

Out of the employed population in the VMD, 56.2% were own-account and unpaid

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[1] of population at statutory working ages

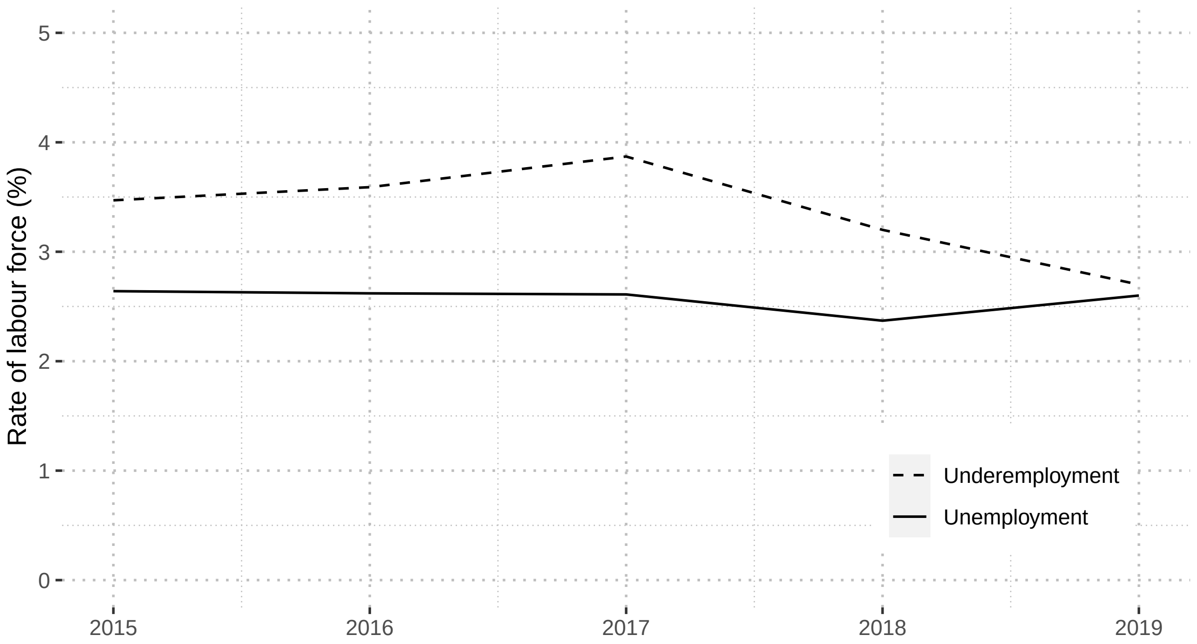

Figure 2.1: Unemployment and underemployment rates in the VMD

Source: GSO, 2020

family workers, whose employment was generally unstable and without any social security, and 40.8% worked in agriculture, forestry, and fishery (GSO, 2020). Monthly income per capita in the VMD averaged around 167.5 USD[2], lower than the national average of 185.2 USD (GSO, 2020). Rural population earned and still earns the majority of their income from agriculture (Kojin, 2020a).

The multidimensional poverty and near-poverty rates[3] were 2.71% and 4.67%, higher than in urban areas but lower than most other agricultural regions (Ministry of Labour War Invalids and Social Affairs, 2020). Landlessness in the region has always been the highest in the country since the French colonial regime, and the median farm size is small (around 0.6 ha in 2014) (Markussen, 2015; T. H. Quang & Nghi, 2016).

These figures capture a predominantly rural region of a developing country, to whose economy agriculture remains crucial. The high natural productivity of the region might have played its part in keeping poverty low, but the VMD on the whole is still the home of less well-off agricultural smallholders, many of whom lack financial security and are subject to the capricious forces of the climate and the market.

2.2.3 Agriculture

Agriculture sustains the VMD. Not only does agriculture directly employ more workers than any other sectors in the region (Figure 2.2), agricultural products are also

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[2] 1 USD = 23,196.47 VND at December 31, 2019

[3] Multidimensional poverty is defined based on both income and access to basic servcies

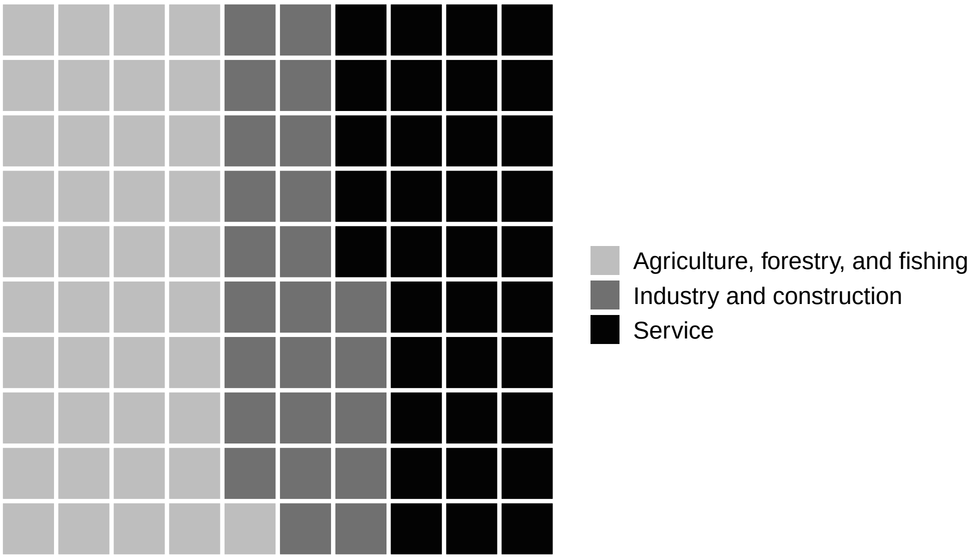

Figure 2.2: Distribution of employed population by sector in the VMD in 2019

Source: GSO, 2019

involved in the majority of the industry and service sectors. 64.1% of the total land in the VMD is agricultural land (GSO, 2020), producing food for 200 million people worldwide (Piesse, 2019).

The main agricultural products in the VMD are rice, fruits, shrimp, and catfish.

2.2.3.1 Rice

Rice is the main staple food in Vietnam, one of the key export products, and the basis of livelihoods in the VMD. Known as the “Rice Bow” of Vietnam, the VMD has a long history of cultivating rice. Before the 20th century, farmers typically harvested one crop per year using traditional planting methods and local rice varieties. Rice yields then were only high enough for self-subsistence. The French colonial regime (1887-1945) boosted the rice expansion by constructing 2,400 km of canals criss-crossing the delta, but rice yields remained low. After the First Indochina War (1946-1954), the introduction of new technologies such as motorised equipments and high yield varieties, along with land reform led farmers to start double-cropping. However, the Second Indochina War (1955-1975) and subsequent state-controlled and collectivisation policies suppressed any intensification attempts, culminating in the record level of food deficit in 1978 (Chiem, 1994; Le Coq, Dufumier, & Trébuil, 2001; Vormoor, 2010).

In 1986, the Doi Moi (renovation) reform programme was launched, liberating the economy and opening up both the inputs import and the rice export markets. This breathed a new life into the rice paddies in the VMD and ushered in an era of rapid growth in rice production. No longer a country that had to import rice to ward off famine in 1977-78, Vietnam became in 20 years the second biggest rice exporter in the world (Le Coq et al., 2001; Vormoor, 2010). Such an achievement puts rice squarely in the top of the government's agenda.

In 1996, the government issued the first policy to develop hydraulic infrastructure for irrigation, transportation, and rural planning in the VMD (Chun, 2015; GVN, 1996). By the early 2000s, the VMD had 11,000 km of canals and around 20,000 km of mostly low dikes, which protect rice paddies against the flood peak during July-August and ensures the double-cropping practice (Triet et al., 2017; Vormoor, 2010). After the historic flood in 2000 that breached the low dikes, the government implemented plans to build high dikes that render large swathes of the region completely flood-free. Tens of thousands more sluice gates had also been constructed to manage saltwater intrusion (ICEM, 2012). This large-scale expansion in water engineering can be considered as a stone that kills two birds: the high dikes and sluice gates help prevent flood and saltwater intrusion while at the same time advancing the government's rice-first agenda. Farmers started to triple-crop in earnest, and from 2000 to 2010 the triple-cropped rice paddies had almost doubled (Kontgis, Schneider, & Ozdogan, 2015).

The intensification in the use of input and cropping patterns, along with the privatisation of production factors, led to an impressive increase in rice yield and cemented Vietnam's position as an important producer in the global rice market (Le Coq & Trebuil, 2005; Vormoor, 2010). However, this high-speed growth came with an environmental price: to keep up with rice intensification and triple-cropping, farmers substantially increased their use of agricultural chemicals, which led to water and land pollution (Kien et al., 2020; Minh et al., 2020; D. D. Tran, van Halsema, Hellegers, Ludwig, & Wyatt, 2018).

The rice seasons in the VMD are Dong Xuan or winter-spring (WS), He Thu or summer-autumn (SA), and Thu Dong or autumn-winter (AW). The WS season coincides with the dry season and thus requires irrigation. It is also the main rice season in the year, accounting for more than 40% of annual planted areas and 45%-47% of annual total production (GSO, 2021). At present, the majority of farmers practice double-cropping, which can be WS-AW or SA-AW. Triple-cropping is practiced mostly in the central area of the VMD, in close vicinity of the Mekong distributaries or canals. Single-cropping is prevalent in the coastal provinces and can use either traditional floating rice varieties which have longer maturity duration (known as Mua in Vietnamese) or high-yield varieties (Hoang-Phi et al., 2020; D. B. Nguyen et al., 2015).

Season	Planting	Harvesting	System	Rice varieties
Winter-Spring	Nov/Dec	Feb/Mar	Irrigated	High yield
Summer-Autumn	May/Jun	Aug/Sep	Rainfed	High yield
Autumn-Winter (Mua)	Jul/Aug	Dec/Jan	Rainfed	High yield or Traditional

Table 2.1: Rice seasons in the VMD

In 2019, the VMD planted 4 million ha of rice[4], produced 24 million tonnes, and exported around 5.7 million tonnes, valued at more than 2 billion USD (GSO, 2020;

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[4] Since there are more than 1 rice seasons in the VMD, the total planted area of rice will always be larger than the total amount of agricultural land

D. K. C. Nguyen, 2020).

2.2.3.2 Fruit

Despite its new status as the top rice producer in the country, in the 1990s the VMD remained one of the poorer regions in the country. This was the result of (i) saltwater intrusion in the coastal area affecting rice crop (van Halsema & Sikkema, 2019), and (ii) domestic rice prices—kept low in the interest of national food security and by a binding export quota (Minot & Goletti, 2000)—and the accelerated growth of manufacturing regions and service-orientated cities.

To rectify the situation, in the early 2000s, the Vietnamese government lifted the export quota (GVN, 2001) and for the first time encouraged the diversification of agriculture (GVN, 2000). Fruits were among the crops into which farmers were encouraged to switch into. The monsoon climate of the VMD was favourable to many tropical fruits such as bananas and mangos, as well as many speciality varieties. Considered more high-value than rice, fruits quickly established themselves in the VMD.

However, the fruits production and value chain in the VMD were and are underdeveloped still. Most fruit orchards are small and scattered around the region; average yields are lower than international competitors such as Thailand and China. A substantial proportion of fruit cultivation is unplanned and spontaneous; farmers chase trends and switch varieties quickly, which often leads to oversupply and rock-bottom prices (Gia Bao, 2021; Hoang, Dinh, Nguyen, & Tacoli, 2008). Moreover, similar to rice farming, fruit cultivation also contributes to water and land pollution due to the heavy-handed use of pesticides and fertilisers.

Fruits are cultivated all-year round, with different varieties having different schedules. In 2018-2019, the VMD had 361,713 ha of fruit cultivation (33.9% of total fruit cultivation areas), and produced approximately 4.3 million tonnes (60%) (Directorate of Fisheries, 2019; Q. M. Nguyen, 2020)

2.2.3.3 Shrimp

Shrimp cultivation in the VMD started in the 1988 with local species (*Penaeus merguiensis* and *Penaeus indicus*). In 1997, production shifted gears with the introduction of black tiger shrimp (*Panaeus monodon*). This resulted in the shrimp boom of the early 2000s that continued throughout the decade: shrimp production jumped from less than 50,000 tonnes in 1995-1990 to 69,000 tonnes in 2000 to 347,000 tonnes in 2010. In 2007, Pacific white shrimp (*Penaeus vannamei*) became more prevalent throughout the VMD and is catching up with black tiger shrimp as the highest-value shrimp species in the region as well as in the country (Pongthanapanich et al., 2019; N. H. Tran, Pham, Vo, Truong, & Nguyen, 2015).

There are four types of shrimp farming system currently practised in the VMD: improved extensive monoculture, intensive monoculture, integrated mangrove-shrimp, and alternative rice-shrimp systems. While there has been a profit-driven trend towards intensification, improved extensive monoculture remains the more prominent system (Pongthanapanich et al., 2019; N. H. Tran et al., 2015). Despite its relatively high profitability, shrimp farming is still a smallholder affair; most shrimp farms range from 0.2 to 7 ha, and grow-out ponds account for 60% of total farm area (Pongthanapanich et al., 2019).

Shrimp farming is a risky business. Most, if not all, shrimp farmers in the VMD have suffered from disease outbreaks, losing up to 80% of production (Pongthanapanich et al., 2019). Drought and typhoons, frequent features of the region, routinely damage stocks and equipment as well as impeding production. A pilot insurance programme implemented by the government in 2011-2013 failed because the amount of compensation requested far exceeded the premium collected (K. A. T. Nguyen, Nguyen, Bui, Jolly, & Nguelifack, 2021).

The environmental impact of shrimp farming is also substantial. Shrimp farming is notorious for its high carbon footprint. Shrimp ponds consume a large amount of energy (Tien, Matsuhashi, & Chau, 2019), destroy and degrade mangrove ecosystems, thereby contributing to land subsidence (Thu & Populus, 2007; Veettil, Quang, & Thu Trang, 2019), pollute water and salinise soil (Kruse et al., 2020). It is evident that current shrimp farming methods are far from sustainable, and the ongoing intensification of shrimp farming would only exacerbate the issues.

In 2019, the VMD had close to 669,000 ha (93% of total shrimp cultivation areas) and produced 753,512 tonnes of shrimp (about 84% of total shrimp production) (Bich Hong, 2019; GSO, 2020)

2.2.3.4 Catfish

Like rice, freshwater striped catfish, or *Pangasianodon hypophthalmus*, also has a long history in the VMD. Traditionally, catfish was reared mainly in the upstream of the Mekong River for household consumption and to supplement income. At this time, wild fish caught from Cambodian waters was used as seed stock and cultivated in small ponds (De Silva & Phuong, 2011).

The expansion and intensification of catfish farming started in the late 1990s and sped up in the 2000s, when agricultural diversification was first encouraged. A Cambodian ban on wild fish capturing in 1994 also helped facilitate the growth of farm-reared seed stock. Intensive pond cultivation gradually superseded traditional pond, cage, pen, and rice-fish cultivations, significantly boosting productivity. Within a decade, catfish production grew exponentially and catfish export values grew 50-fold (T. P. Nguyen & Dang, 2010). Vietnam soon became so big in the international catfish market that it sparked a still unresolved trade dispute with the US (Margolis, 2018; Mydans, 2002).

At present, catfish is cultivated intensively and mostly in the VMD. Ponds are concentrated along the upper stream distributaries and remain active throughout the year (De Silva & Phuong, 2011). The growth period of catfish is about 6-7 months, and most farmers employ staggered stocking to ensure continuous crop (Phan et al., 2009). Unlike shrimp, catfish farming has relatively low environmental impacts: catfish farming consumes less water and discharge much fewer pollutants into the river waters (Anh, Kroeze, Bush, & Mol, 2010; R. Bosma, Anh, & Potting, 2011; Little et al., 2012). However, despite its successes, an unstable market, tariff as well as non-tariff barriers to international trade, and disease issues are casting a shadow on the sector.

In 2019, the VMD had 6,600 ha of catfish pond and produced 1.42 million tonnes of catfish (45% of global production), reaching an export turnover of 2 billion USD (Food and Agriculture Organization (FAO), 2019, Vietnam Association of Seafood Exporters and Producers (VASEP), 2020, 2021).

2.3 Climate change challenges

For the past 50 years, the VMD has felt the heat of climate change first-hand. From 1970 to 2007, the mean temperature in the VMD increased by 0.6°C and mean rainfall by 94mm—much faster rates than those over the previous 30 years (Deltares, 2011; World Bank, 2017). Taking into account these rates, it is expected that by the end of the century, mean temperature will rise by 2.0-2.6°C while mean rainfall will increase by 1.5-2% during the rainy season and decrease by 10-22% during the dry season (P. K. Nguyen, 2009). From 1993 to 2014, mean sea level over the South China Sea increased by 4.05±0.6 mm/year and is expected to increase by 0.45-0.77m by the end of the century (T. Tran et al., 2016). Over the same period, extreme events such as severe droughts and strong typhoons also showed increasing trends (T. Tran et al., 2016).

These climate change impacts have been exacerbating the existing environmental problems, both naturally and anthropogenically driven, in the VMD. Given the very low topography of the region and the severe subsidence caused by mangrove degradation, excessive groundwater extraction, sand mining, and the upstream construction of hydraulic infrastructure, thermal sea level rise has been shrinking and would eventually sink the VMD (Jordan, Visscher, Dung, Apel, & Schlurmann, 2020; P. S. Minderhoud et al., 2017). Sea level rise and changes in rainfall pattern, along with human activities and the increase in drought events, can also reduce groundwater (Shrestha, Bach, & Pandey, 2016), increase the annual flooding and salinisation in terms of size, intensity, and duration (Balica, Dinh, Popescu, Vo, & Pham, 2014; Eslami et al., 2019; C. T. Nguyen, 2016; Toan, 2014; Triet et al., 2020; Vu, Yamada, & Ishidaira, 2018; Wassmann et al., 2019; Whitehead et al., 2019), and increase incidences of infectious diseases in both humans and animals (Marcogliese, 2008; Maulu et al., 2021; H. X. Nguyen et al., 2017).

Significant changes in weather and hydrological patterns affect agriculture more than any other sectors. Thus, climate change and the resulting deterioration of land, water, and other natural resources spell trouble for the VMD and its people, who are extensively dependent on agriculture. A 1 m rise in sea level would flood 100% of the delta during the rainy season (instead of the present 50%), causing an economic loss of 17 billion USD in total (in 1998 USD) (Zeidler, 1997). The same rise is also estimated to sink 11,000 km of roads and 574 km of dikes, wrecking inputs and outputs transportation as well as allowing more saltwater to intrude (ICEM, 2012). Under the high emission scenario[5], the most pessimistic forecasts suggest that by 2050 increased salinisation is projected to cause a loss of 37.2% of the area of land suitable for rice farming, which equates to a loss of roughly 9 million tonnes of rice, and 11% of the catfish farming area, which equates to 156,200 tonnes of fish (A. T. Dang, Kumar, & Reid, 2020; Trieu & Phong, 2015). That is more than 2 billion USD worth of rice and 344 million USD worth of catfish[6] in 2019 export prices. A more positive forecast still puts the loss of rice yield caused by severe salinisation and flooding at 3.9 million tonnes, which is no less than 1 billion USD worth of rice (Yen, Quyen, et al., 2019). Production losses of such considerable magnitude are disastrous not only to the regional population but also to the entire country, whose food source depends in no small part on the region, and to the global commodity markets, wherein the VMD ranks among the big players.

Some of the losses attributable to climate change and its impacts have already been realised. Between 2001 and 2005, the transport sector suffered damages of about 167 million USD[7] from extreme weather events (ICEM, 2012). In 2011, the VMD suffered from severe flooding, losing 250,000 ha of rice and incurring an economic loss of 260 million USD (Mekong River Commission, 2015). During the dry season of 2015-2016, a historic drought and saltwater intrusion event cost the VMD 360 million USD, damaged 339,200 ha of rice (approximately 22% of the total planted area of the WS rice season), 29,277 ha of fruit (approximately 10% of the total planted area), and 79,000 ha of shrimp (approximately 11% of the total farming area) (Mekong River Commission, 2019; N. A. Nguyen, 2017). For a region whose people earn on average less than 200 USD per month, these numbers represent losses of unimaginable and, for many farmers, unrecoverable proportions. Most recently, the dry season of 2019-2020 witnessed an even worse drought, with 154,771 ha of rice and more than 300,000 ha of other crops expected to be gravely affected (International Federation of Red Cross and Red Crescent Societies, 2020). The coincidence in time with the COVID-19 pandemic exacerbated the impacts of the drought event, threatening the lives and livelihoods of hundred thousands of households as well as disrupting the global markets.

2.4 Agricultural and climate change policies in the VMD

The Vietnamese government has not been slothful in addressing the challenges that climate change poses. Internationally, Ha Noi has been signalling their willingness and commitment to combatting climate change by signing, rectifying, and implementing international conventions and treaties as well as global strategies. Vietnam is a signatory of the United Nations (UN) Framework Convention on Climate Change (1992), the Kyoto Protocol (1998), the ASEAN Agreement on Disaster Management and Emergency Response (2009), the Paris Climate Agreement (2016), and has committed to the Hyogo

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[5] Known as RCP8.5 in the literature, this is the “business as usual” scenario wherein no concerted efforts are employed to mitigate climate change, i.e. the worse-case scenario

[6] The export price for a tonne of catfish fillet in 2019 was 2,200 USD (FAO, 2020)

[7] This is equivalent to 2,571 billion VND at the exchange rate of 1 USD = 15,429 VND at December 31, 2005

Framework for Action (2005) and the Sendai Framework for Disaster Risk Reduction (2018).

Domestic response to climate change has also been keeping pace with international engagement. Since 2006, climate change has always featured prominently in Vietnam's Five Year Plans, a series of socio-economic development directions central to the country's political and economic environment. The first formal document relating to climate change is the National Target Programme to Respond to Climate Change, which was promulgated in 2008 and which sets out the response framework for all sectors. The main national document, the National Strategy on Climate Change, was approved by the Prime Minister in 2012. This document delineates, among other things, the main objectives as well as the priorities for all national and regional climate change efforts hereafter. In 2013, Ha Noi codified climate change response obligations into the Constitution (The Constitution of the Socialist Republic of Vietnam, Chapter III, Article 63) and since then, numerous projects and policies ranging from greenhouse gases reduction to green growth have been developed and executed to various degrees of success and efficiency.

As the climate change hotspot of the country, the VMD has received much attention from the government. Multiple remedial, mitigation, and adaptation initiatives have been designed and implemented in the region, many of which are cooperative work with foreign governments and organisations, such as the Project for Climate Change Adaptation, implemented by Japan International Cooperation Agency (JICA) (JICA, 2013), and the Mekong Delta Plan, formulated in technical and financial partnership with the Dutch government (GOV, 2013). The measures proposed and carried out can be divided into two groups: structural measures, which involves the rehabilitation and development of infrastructure such as hydraulic constructions, and non-structural measures, which concern changes in farming practices and land use.

2.4.1 Issues

All in all, it is evident that there is no lack of political will when it comes to preserving the "rice bowl" of Vietnam against climate change. After all, adverse weather conditions are not novel phenomena; the country, and especially the VMD, has been locked in a struggle with nature for most of history. Climate change may be the biggest environmental problem yet, but Ha Noi has proved themselves keen to meet the challenge head-on.

However, keenness does not always translate into efficacy. Despite having devoted considerable attention and resources to the cause, the government has yet to produce much result. Throughout the country, environmental degradation continues to happen at an alarming rate (Giang & Gia, 2019; Hoi, 2020), and natural disasters have become more and more frequent (Institute for Economics & Peace, 2020). The VMD is among the worst-suffered: regardless of all the dikes and sluice gates built, regardless of all changes made to land-use and crop calendars, the region was and remains particularly ill-equipped to handle climate change and its repercussions (see Section 2.3).

This regretful lack of efficacy in Vietnam's climate change policies has roots in both policy formulation and policy implementation. Concerning policy formulation, the chief issue is one of contradictory goals: the government is prone to form policies that compete with one another in effects desired. For instance, in the early 2000s, the government called for agricultural diversification, acquiescing that land with low rice-productivity should be used to cultivate other, more suitable crops (GVN, 2000). However, at the same time, the government also built dikes sluice gates in the VMD to control salinity in a move to promote freshwater-based rice farming and chase rice export-fuelled growth (Baran, Jantunen, Chheng, & Hoanh, 2010). This created a) uncertainty about the development pathway of the country, and b) tension between different stakeholders, in this case between rice farmers and shrimp farmers. The conflict came to a head when shrimp farmers opened the sluice gates and let saltwater into the rice paddies, damaging properties and undermining both policies (Baran et al., 2010).

A related issue is the excess of VMD development plans proffered or in progress. These plans might not have contradictory goals, but many of them advocate measures that are mutually incompatible. The Mekong Delta Plan, approved by the government, reviews in its appendix 7 other development plans also approved by the government, some of which go completely against the Plan's recommendations and would have to be heavily revised or abandoned (GVN, 2013). The Mekong Delta Plan itself also goes head to head with JICA's Project for Climate Change Adaptation, which was conducted during the same period and whose proposals are already under implementation in parts despite the project not being officially approved (JICA, 2017). These competing plans are a waste of resources that should have been allocated to more fruitful use.

Regarding policy implementation, there are also two issues. The first issue is the lack of public compliance. Policy enforcement in Vietnam is notoriously lax (Ha, Dieperink, Dang Tri, Otter, & Hoekstra, 2018), with complicit local officials a widespread issue. Consider the case of the "3-3-2 rice cycle" policy in the VMD. Due to the newly constructed high dikes, sediment-loaded floodwater is completely absent from many paddy fields. Without new sediment, land would lost its fertility. Recognising the problem, in 2007, An Giang Province (one of the VMD's 13 provinces) issued a policy requiring triple-cropping farmers to cease rice production for one season and allow floodwater into their fields every three years, i.e. producing 3 crops in the first two years of the cycle and 2 in the third year (An Giang Province People's Committee, 2007). However, in tacit agreement with local officials, the majority of farmers have not implemented the policy: many communes still practice triple-cropping continuously despite its detrimental impacts on land quality (Chapman, Darby, Hong, Tompkins, & Van, 2016). The main reason given to this non-observance is that the policy goes against farmers' motivations: complying with the "3-3-2 rice cycle" policy means losing additional profits that cannot be recovered through alternative livelihoods or possible benefits that the policy allegedly brings about, and no one wants that (An Giang Province People's Committee, 2007).

The second issue is the presence of unintended and unforeseen consequences. Agricultural policies and climate change adaptation measures in the VMD are rather prone to produce side-effects that lie in the blind spots of policy makers. For example, rice intensification policy has as its goal poverty reduction, yet it has also incurred large social costs. To increase rice production substantially requires sizeable investments, which smaller farmers cannot afford. Thus under rice intensification policy, the rich become richer and the poor poorer; the level of social stratification and inequality increases (Chapman & Darby, 2016; T. D. Vo, 2021). Farmers also become more stressed and exhausted, as they are required to engage in intense production all year round, pushed by quotas set by the government (T. D. Vo, 2021). Similarly, the construction of dikes and sluice gates to control flood and saltwater intrusion drives out-migration (T. A. Tran, 2019) reduces the opportunities for agricultural diversification (Garschagen, Diez, Nhan, & Kraas, 2012; T. D. Vo, 2021), negatively affecting the food source and thus the nutrition of poor households (V. K. Nguyen, Pittock, & Connell, 2019), and reduces agricultural productivity in the long-run (Pham, 2011).

While we separate the issues into distinct categories, there is a high degree of overlap and interconnection between them. Low public compliance can be considered an unintended consequence, although we choose to set them apart to highlight local officials' condoning of such behaviours. Issues in policy formulation are also partially responsible for issues in policy implementation. However, it would not be prudent to argue that a well-formulated policy would completely solve the issues in policy implementation. There are factors at play here that lie beyond the scope of what good policy formulation can achieve (regardless of what "good" means here), such as menial corruption, insufficient resources, or the extant institutional framework.

2.4.2 Causes

Nevertheless, for issues in policy formulation as well as for problems in policy implementation that arise from these issues, we identity two main causes. First, there is very little coordination among sectors and among levels of authorities. This is a phenomenon well-documented (GVN, 2013, Ha et al., 2018; Hutton et al., 2021; Q. H. Nguyen et al., 2020; Smajgl, Toan, et al., 2015; Waibel, 2010) and even admitted to in government's official documents (see GVN, 2017). Agriculture and climate change are complex, multifaceted matters; they concern not only their respective sectors like environment and natural resources but also various others such as economics, transport, finance, education. Yet traditionally, each ministry is only in charge of one specific aspect. For example, while the Ministry of Natural Resources and Environment (MONRE) is the main ministry at the helm of managing response to climate change, it is not involved in the setting of economic and agricultural strategies, despite both sectors being crucial facets of climate change problems and responses. It is also not responsible for flood recovery nor water management in the VMD, which are under the oversight of MARD, the Ministry of Transport (MOT), and the Ministry of Construction (MOC) (evident in GVN, 2000, 2012, 2013). The Mekong Delta Plan is a collaboration between MONRE and MARD, but the latter also commissioned the JICA's Project for Climate Change Adaptation, which does not take into account the Mekong Delta Plan's recommendations, indicating ineffective communication and confusion about their respective responsibilities between these two ministries (Waibel, 2010). Without horizontal coordination, cross-sectoral considerations are far and few between, locking each sector away from one another and separating the human system from the environmental system. As a result, duplicate plans run rife and reckless, and economic policies are unconcerned with their impacts on the environment, competing water management measures unsure of their economic reverberations, and land-use planning uncertain about how they affect the long-term livelihoods of farmers.

There is a similar lack of coordination between the national, regional, provincial, and local authorities. The lack of public compliance with the "3-3-2 rice cycle" rule is but one example wherein local officials refuse to enforce policies formed by authorities higher up in the hierarchy. In addition to central-formulated plans, each province also has their own land-use and water management plans, which again results in too many plans but little attention paid to broader impacts (Ha et al., 2018). Despite the top-down planning approach to policymaking, a common feature of unitary governments, the links between each tier of the hierarchy are tenuous on account of the cumbersome institutional structure and the stark separation between the higher and the lower tiers (Ha et al., 2018; Waibel, 2010). The result is that information cannot travel fast and freely between each tier, short-circuiting communication and cutting off the planning central from the happening grounds.

The second cause of policy issues in the VMD is the lack of an effective policy impact assessment method. Many ex-ante assessments are a priori and purely qualitative; quantified impacts are only estimated in ex-post assessments. For the fewer quantitative ex-ante assessments, the most prevalent method is cost-benefit analysis grounded in standard neo-classical partial and general equilibrium models, with a particular focus on short-term monetary impacts (as an example see the project assessments submitted to the JICA's Project for Climate Change Adaptation 2013). For something as complex and uncertain as the relationships between humans and the environment, this method alone is inadequate for four reasons. First, cost-benefit analyses, or at least those carried out in the VMD, are deterministic impact-wise. The inherent unpredictability and the co-evolution of intertwined systems like the human and environmental systems suggests that long-term consequences may differ greatly from short-term ones. Yet in these analyses costs and benefits are often established a priori based on theoretical works and/or experience; the trajectory of the outcomes is pre-determined. This leaves no room for impacts that appear further down the line and makes the analyses vulnerable to unintended consequences.

Second, this type of assessment has no explicative power. The main purpose of cost-benefit analysis is to present quantitative estimations for decision-making purposes. Causal processes and feedback mechanisms are not studied and consequentially left out of the policy formulation process.

Third, cost-benefit analyses are often performed from the top down. In other words, the analyses adopt the perspectives of the national or at the lowest the regional authorities instead of the perspectives of the people. This could lead, and has led, to a misalignment in interests between those who make policies and those who the policies ultimately impact.

And fourth, heterogeneity, both human and environmental, is ignored. The inputs of the assessments are non-random, aggregated or average data and information provided by government staff and experts (Keskinen, 2008; H. N. Nguyen et al., 2015). But humans and the environment are heterogenous; each individual farmer has their own set of attributes, each plot of land its own properties. Not every farmer would respond to policy interventions the way a theoretical "representative" farmer would. Thus, the distribution of impacts, often not uniform as demonstrated in the case of the rice intensification policy, is not considered. Together with the horizontal and vertical disconnections mentioned above, these weaknesses in impact assessment create a knowledge gap regarding how a nationally-formulated policy would actually function on the ground, especially ex-ante and with a long horizon, which in turn generates policies that are antagonistic to the needs and motivations of the people, which drives down public engagement and drive up unintended consequences.

While facilitating coordination among sectors and among levels of authorities is not within the job scope of academic researchers, it is our responsibility to develop and adopt an assessment method that can effectively fill the knowledge gap. Such a method must be able to explore the dynamics between policies, people, and the settings wherein they are situated, to have a long-term, bottom-up perspective and micro-data as its inputs, and to study policies ex ante. The most suitable method should also be able to reach across sectors and hierarchies, encouraging collaboration and coordination. Of course a tool alone cannot solve everything, especially when the problem at hand involves many stakeholders with different interests. But it is the first step towards the right direction that can be taken readily. We also do not advocate replacing the traditional policy impact assessment methods with a new one. Qualitative assessment and cost-benefit analysis have their own values, which can be greatly enhanced with the complement of an integrated method. This is also not to say that there has never been any attempt to develop integrated policy impact assessment methods in the VMD. As climate change grows more complex and imminent, the call for adaptive and effective policies grows more urgent and has been tentatively met. There are recent studies using different theoretical and practical tools to assess past, current, and possible policies (see Section 3.2). However, these studies are still not the norm, and there remains merit in the search for a suitable method.

2.5 Summary

The big numbers in this chapter demonstrate the importance of agriculture and aquaculture in the VMD. To the people of the VMD, most of whom live a frugal life in rural areas, rice, shrimp, and fish are the backbone of their livelihoods as well as the staples in their diet. Economic liberalisation and infrastructure development have turned these crops into engines of growth, enabling hundreds of thousands of people to escape poverty and transforming the VMD into a key national and regional economic hub.

However, climate change is threatening these achievements. In the 2010s alone the VMD has experienced natural phenomena more severe and more often than ever before. This has translated into economic losses of greater magnitude and higher frequency. The relevant numbers presented here belie the hardship that farmers in the region have endured and will have to endure in the near future given the alarming trend of climate change.

In this context, public policies are expected to play a bigger role in overseeing and coordinating the efforts to mitigate the impacts of and adapt to climate change, especially in a climate-sensitive sector such as agriculture. However, the Vietnamese government does not have a great track record in developing policies that effectively manage the agriculture sector in general. Agricultural responses to shocks like climate change are also very much lacking. This is the result of many issues in the processes of policy formulation and policy implementation, many of which can be attributed to a lack of efficient policy impact assessment methods. We believe that the development and adoption of a more suitable assessment method therefore can help address some of the issues and provide a concrete knowledge base on which more effective policy interventions can be designed and deployed.

To fulfil these objectives, researchers have been busy at work. The next chapter will provide a summary of the assessment methods that have been applied to the VMD and argue why, out of these methods, ABM is the more suitable one.

Chapter 3

Agent-based modelling as a suitable impact assessment method

3.1 Introduction

The most commonly used method to assess agricultural policies in the VMD is cost-benefit analysis grounded in standard neo-classical partial and general equilibrium models. However, as climate change adds more variables to an already complex system, there is a need for an assessment method that is more integrated, favourably disposed towards complexity and its retinues, and sufficiently accommodating so as to coax adoption.

There have been many assessment methods proposed and applied to the problems of the VMD, many of which are extensions of well-known methods or techniques borrowed from other fields. Each method has its own strengths and weaknesses, but given our circumstances and requirements, ABM appears to be the most promising. With a conceptual foundation in complexity theory and an agent-centric framework, ABM is a powerful methodology that can account for heterogeneity and unintended consequences, is flexible and modular, and has strong simulation capability that can produce highly detailed analysis.

To argue for the values of ABM, we begin this chapter by briefly introducing and appraising the suitability of three other methods, namely extended cost-benefit analysis, Bayesian modelling, system dynamic modelling. Then we present in more detail the conceptual construction of ABM and why it is singularly suited to our needs. Finally, we discuss the limitations of ABM.

3.2 Integrated impact assessment methods: a brief review

As the relationship between humans and the environment in the VMD becomes more complex and strained, effective policies are urgently required. Researchers have risen up to the challenge and found ways to incorporate more data and perspectives in their assessments in an effort to (i) attain a more rounded picture of the current situation, and (ii) forecast policy impacts in a wider and further horizon. Of the majority of studies already conducted, there are four notable methods: extended cost-benefit analysis that uses partial equilibrium models, Bayesian modelling, system dynamic modelling, and agent-based modelling.

3.2.1 Extended cost-benefit analysis using partial equilibrium models

As its name suggests, extended cost-benefit analysis employs the familiar method of quantifying and weighing the positive and negative impacts of a policy using partial equilibrium models, but extends it to overcome many inherent limitations of traditional cost-benefit analysis and how it is used in the VMD and in Vietnam, such as the mono-sectoral focus, the short-term bias, and the deterministic nature inherent in the method. For example, Tran et al. (2019) look beyond immediate costs and benefits for the water management sector and consider the delta-wide social and agricultural externalities of a high-dike system in the VMD in the medium term. Danh and Khai (2014) include uncertainty into the analysis framework by considering the range of values that the variables in the model can take and their probability distributions. Kam et al. (2012) disaggregate the cost-benefit analysis, bring it down to farm level, and extrapolate data for the period of 2021-2050.

While these extensions are positive developments, they still have drawbacks. The extensions are customised to address selected weaknesses of the traditional cost-benefit analysis in an ad hoc manner. Therefore, each extension still retains the weaknesses that they are not designed to address. Tran et al.'s (2019) multi-dimensional, medium-term analysis and Danh and Khai's (2014) risk framework remain top-down and non-explicative, with aggregated data as inputs and aggregated costs and benefits as outputs. While Kam et al.'s (2012) farm-level approach does look into farmers' decision-making and adaptation processes, it still relies on the assumption of homogenous farm characteristics and behaviours and cannot account for heterogeneity. All three analyses are still deterministic, using pre-established costs and benefits. None looks into the co-evolution of the human and environmental systems in different policy scenarios.

3.2.2 Bayesian modelling

Bayesian modelling is the broad name for a class of methodology that seeks to take uncertainty into consideration by using Bayesian probability. In the VMD, Bayesian modelling has been used to develop the BayFish-Bac Lieu model, which aims to optimise the water control regimes in Bac Lieu Province (Baran, Jantunen, & Chheng, 2006; Baran et al., 2010). This model comprises a Bayesian belief network that represents the probabilistic relationships between variables. Both the structure and the attached probabilities are built from information and data supplied by local farmers and officials as well as academics conducting relevant research through a series of consultations. The results are the likelihoods of specified outcomes in different sluice gates operation scenarios.

This model certainly ticks many of our checkboxes. The researchers build their analysis and the model from the bottom up and involve the contributions of as diverse a group of stakeholders as possible. As a result, the model manages to capture many consequences of different sluice gates operation strategies that a priori theoretical research could not reveal. The model is explicative and cross-sectoral: it provides causal links not only between the human system and the environmental system but also between different parts within the systems, such as between water and soil management. Being Bayesian, the model is also sensitive to uncertainty.

However, the model still falls short in several aspects. Like any other Bayesian models, it relies on prior distributions to compute the final results. Any degree of heterogeneity in micro-data that the model considers has to be weighed against pre-formed opinions of experts. Moreover, as the model's parameters and outputs are probabilities computed from available information, it does not concern itself with dynamics. This means that it only offers a snapshot of the current situation, does not track the tempo evolution of variables, and has to be recalibrated every time the situation changes (Baran et al., 2010). Therefore, the model is confined to short-term analyses only and better suited for fine-tuning existing policies rather than grand planning.

3.2.3 System dynamics modelling

System dynamics is an approach and a modelling methodology designed specifically to unpack complex systems and uncover their inner workings. The systems under research are broken down into core elements: variable values accumulated into or depleted from *stocks*, *flows* or rates of change of such stocks written in the forms of differential equations, and *feedback loops* that connect the stocks together. The concurrent processes that drive the accumulation or depletion of stocks is the engine that drives the system. Simulations of the model shows the behaviours of the engine and of the system over time.

Chapman and Darby (2016) use the system dynamics approach to model the workings of VMD farmers' economic system. The unique selling point of their model is the integration of fluvial sediment deposition as endogenous processes. This gives them the means to explore the economic impacts of alternative rice cropping patterns, of the "3-2-2 rice cycle" mentioned in Section 2.4.1, and of the idea concerning strategic flooding to maximise sediment deposition on different groups of farmers stratified by farm size as a proxy for wealth.

Chapman and Darby's model is by nature cross-sectoral and highly explicative. It is also able to approximate heterogeneity and discover the unintended consequence of the rice intensification policy on inequality by disaggregating the representative farmer and running independent simulations for each disaggregated group. In doing so they bypass some of the restrictions normally found in top-down, deterministic differential equation models like theirs. However, since wealth groups are treated separately, there is no interaction between farmers of different groups. This potentially leaves out important dynamics that may conceal more impacts that are not hypothesised beforehand. In cases where a higher degree of heterogeneity is required, this technique of population disaggregation would also prove difficult to manage.

3.2.4 Agent-based modelling

Agent-based modelling is also a methodology that studies complex systems. In an agent-based model, a system is reconstructed from individual *agents*—entities that are situated in an environment and possess properties, states, and behaviours—and their interactions, which are governed by simple rules (Wilensky & Rand, 2015). From these micro interactions arise macro phenomena such as aggregated patterns of behaviours or systemic attributes, which are the objects that the modeller wants to recreate or predict.

In Vietnam, Castella et al. (2005) synthesised the SAMBA-GIS model from a theoretical model, an ABM, a role-playing game, and a geographic information system (GIS). SAMBA-GIS is able to identify similar localities where similar policy interventions can be implemented. Le et al. (2008) design the LUDAS model that links the human and the environmental systems together and uses a decision-making algorithm to simulate the impacts of policies on land-use choices[1]. The decision-making algorithm is derived from a combination of utility maximisation equation rooted in bounded rationality and heuristic techniques. They apply the model to an upland watershed in central Vietnam and analyse the trade-offs between agriculture development and forest conservation policies.

Quang et al (2014) use Schreinemachers and Berger's (2011) MP-MAS model to explore the relationship between soil quality, household incomes, and soil conservation choices, as well as how payments for ecosystem services (PES) would affect them. What sets the MP-MAS model apart from other ABMs is its inclusion of an innovation diffusion algorithm, which combines social contagion effect with individual economic evaluation of new innovations.

In the VMD, Joffre et al. (2015) follow in Castella et al.'s footsteps and combine participatory gaming with an ABM to explore the development paths of shrimp aquaculture and the effectiveness of PES and extension services. Smajgl, Toan, et al (2015) uses

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[1] Many of the models we refer to as ABMs are classified by their authors as multi-agent system (MAS) models. Strictly speaking, ABM and MAS modelling are related but separate concepts. However, the features they share matter more to our study than their differences, and some researchers do appear to use the two terms interchangeably. Therefore, we decide to include MAS models under the ABMs rubric.

ABM to examine household income and crop production to understand household-level vulnerabilities to sea level rise. To help optimise land-use planning in the region, Drogoul et al. (2016) build an ABM with environmental, economic, and social sub-models that can be substituted in and out as desired. While the researchers have not used the model to analyse policy impacts, they have test-run several combinations of the sub-models on how farmers' responses to saltwater intrusion result in historic land-use changes in Ben Tre Province as proof of the flexibility and efficiency of their model.

ABM appears to be what we are looking for in an impact assessment method. Its philosophy centres on the concept of emergence, which refers to the process wherein interactions between individuals generate collective attributes that the individuals do not have on their own. This bottom-up approach throws open the door to analyses that can make allowances for unintended consequences and heterogeneity. As the goals of ABM are not only the end states but also the dynamics that result in the end states, it has a high explanatory power. The architecture of ABM which include agents embedded in spatio-temporal context also lends itself nicely and naturally to the integration of the human and the environmental system that we require.

ABM certainly is not without its challenges. And there are many aspects at which other assessment methods are more competent. For example, ABM requires and is dependent on a large amount of data inputs; in cases where policies are well-defined and have a restricted and predictable set of outcomes (e.g. the ban on sand-mining in the VMD), traditional cost-benefit analysis is a better choice, since it costs less to set up, is more parsimonious in terms of data, and is more straightforward to implement due to its familiarity.

With this in mind, we contend that ABM is the methodology that fits our needs the best. To provide more arguments for this proposition, we will dedicate the following sections to delve into the background as well as the advantages and limitations of ABM and the use of ABM in agricultural and adaptation policy assessment.

3.3 The development of ABM in agricultural policy assessment

The use of ABM in the agricultural sector can trace its roots back to the 1960s, when scholars like Richard Day raised questions about the aggregation problem in agricultural production economics (R. Day, 1963). To circumvent the issue of aggregating individuals that are dissimilar and to incorporate behavioural economics into farm analysis, R. H. Day and Singh, 1975 designed and applied a recursive linear programming model to the green evolution in Punjab, India over a 14 year period.

In 1997, Balmann, 1997 continued this line of research with his cellular automata framework, which adds a spatial dimension to dynamic models to investigate structural changes in agriculture. Drawing on this study, T. Berger, 2001 developed MAS-CA, the precursor of MP-MAS, a model that brings economics and hydrology together to assess the impacts of Mercosur on technological diffusion and economic outcomes in Chile.

The use of ABMs in agricultural policy assessment started to pick up steam in the 2000s. Researchers all over the world designed and applied ABMs to a wide range of policy interventions. In 2006, Happe, Kellermann, and Balmann, 2006 expanded Balmann's cellular automata model into the Agricultural Policy Simulator (AgriPolis) and used it to analyse the impact of proposed changes in the Common Agricultural Policy on the structures of European farms (Happe, Balmann, Kellermann, & Sahrbacher, 2008; Happe, Schnicke, Sahrbacher, & Kellermann, 2009).

While AgriPolis is capable of simulating an entire agricultural system including factor markets and the environment, it does not include the environment into the feedback loops. In other words, the environment does not respond to policy interventions or changes in farm structure; the environment system, though coupled with the human system, remains exogenous. Several other models seek to tackle this issue. Becu, Perez, Walker, Barreteau, and Le Page, 2003 build CATCHSCAPE, an *"integrative, spatially distributed, and individual based"* model that simulates a water catchment in northern Thailand and their natural resources management schemes. CATCHSCAPE endogenises both the decision-making processes and the biophysical dynamics by incorporating CATCHCROP, a model that uses crop choices to compute water demand and from there, to simulate crop yields (Perez, Ardlie, Kuneepong, Dietrich, & Merritt, 2002). Similarly, Schreinemachers and Berger's 2011 MP-MAS model and Le et al.'s (2008) LUDAS also use biophysical models to simulate resources conditions from farming decisions.

With the publication of seminal models like AgriPolis, MP-MAS, and LUDAS, there has been a surge in ABMs in agriculture. The looming gravity of climate change and its repercussions means that for the past decade, ABM has been used to research how farmers make decisions in the face of heightened risks of droughts (see for example Hailegiorgis, Crooks, and Cioffi-Revilla, 2018; Wens et al., 2020) and floods (Malanson et al., 2014; Nabinejad & Schüttrumpf, 2017), and to assess climate change mitigation and adaptation policies such as PES (An et al., 2020; Chen et al., 2012; Huber et al., 2013; Miyasaka, Le, Okuro, Zhao, & Takeuchi, 2017; Smajgl, Xu, et al., 2015), carbon reduction instruments (Carauta et al., 2018; Ng, Eheart, Cai, & Braden, 2011; Ng, Wayland Eheart, Cai, Braden, & Czapar, 2014), or sustainable energy development (C. Brown, Bakam, Smith, & Matthews, 2016; Troost, Walter, & Berger, 2015).

Empirical approaches to decision-making processes in ABMs have also been gaining traction. A decision-making process is empirical when it is derived from comprehensive data, either quantitative or qualitative or both, instead of a theoretical foundation. The data can be obtained from sample surveys and interviews (Shahpari, Allison, Harrison, & Stanley, 2021) or from participatory methods such as workshops (Belem, Bazile, & Coulibaly, 2018; Joffre et al., 2015; Pope & Gimblett, 2015) or role-playing games (Castella, Trung, & Boissau, 2005; Joffre et al., 2015; Naivinit, Le Page, Trébuil, & Gajaseni, 2010). By involving stakeholders in model development and calibration, the empirical approaches bring ABM even closer to the "bottom", maximising the methodology's ability to account for heterogenous objectives and behaviours in the human system. However, by giving priority to data over theories, these approaches also open themselves up to criticism.

Over the span of 40 years, ABM has become bigger and stronger, with new focuses and bonuses. However, a look through all the models mentioned in this section and beyond shows us that ABM endures and flourishes because of the same advantages that attracted researchers four decades ago: the bottom-up philosophy that allows for heterogeneity and unintended consequences, the agent-centric framework that facilitates modularity and boosts flexibility, and the simulation capability that explores different scenarios over time and space. These are the topics of the next section.

3.4 Why ABM?

As implicated in the previous sections and chapter, for the purpose of agricultural and climate change policy assessment, analytical models have certain limitations. They are generally plagued by the well-known problems of aggregation and overspecialisation, and restricted in their ability to model inter-agent interactions, spatial dimensions, and heterogeneity (T. Berger, 2001; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003). ABM, when competently used, can address these weaknesses. We identify 3 key strengths that are intrinsic to ABM: the bottom-up philosophy, the agent-centric framework, and the simulation capability.

3.4.1 Bottom-up philosophy

The foundation of ABM is *aggregate complexity*: the idea that the complexity of a system is born from the relationship between agents—components of the system—and simple behavioural rules (Manson, 2001). To quote the physicist Murray Gell-Mann: *"surface complexity arises out of deep simplicity"* (Lewin, 1992, pg. 14). A system then is characterised less by agents and their attributes and more by how agents interact with other agents and with their environment. In that vein, an economy is less about the people and more about how they produce and trade goods and services. Moreover, agents and their relationships are not indistinguishable. Agents with similar attributes can form various different systems and sub-systems depending on the types of relationships they have with one another and with their environment (Manson, 2001). A system of buyers-sellers is different from a system of sellers-sellers, even if all people are homogenous. A system of sellers-sellers wherein the sellers are spaced far apart is different from a system made up of the same sellers who are situated close together.

That a system arises from agent interactions leads us to *emergence*. An attribute of a system is deemed emergent if it cannot be analytically traced back to any attributes of the agents in the system. Irrational system-wide behaviours such as herding can arise from investors behaving rationally (i.e. fundamental-driven spurious herding, see Bikhchandani and Sharma, 2000). In other words, there can be no isomorphism between certain system attributes and agent attributes. This is the logic behind the age old adage: *"The whole is greater than the sum of the parts"*. Emergent attributes are hard to predict and harder to control. Because of their nature, it is hard to analytically foresee the existence of emergent attributes from agent attributes alone. It is also extremely difficult to anticipate changes to emergent attributes from changes made to agents in the long run, due to the feedback loops present in the interactions between agents themselves and between agents and the system. Agents can adapt to interventions in ways that alter their interactions with one another beyond what can be predicted, and this is even more true for heterogenous agents, whose interactions can modulate widely. This ultimately leads to unexpected system-wide changes. Such changes then affect agents, prompting them to adapt again and compounding the unexpectedness.

ABM is an effort to study systems while keeping in mind complexity and emergence. This method trades in the traditional top-down, system-level modelling approach, along with its averages and aggregates, its closed-form solutions and its assumptions of equilibria, for the ability to observe the generation of systems from dynamically interacting agents. As the name suggests, agents are the drivers of ABMs. Situated in space—an environment specified beforehand—and time, they are equipped with a set of attributes and simple rules that govern their behaviours. When the model is run, each individual agent would evaluate environment inputs and behave according to their rules. There is no central planner; agents are therefore autonomous. The behaviours of agents alter the environment, and in the next iteration of the model, they will evaluate their altered environment and change their behaviours accordingly. The model runs for a specified number of iterations, after which the modeller can inspect the emerged states of the system.

Armed with this bottom-up approach, ABM can accomplish two crucial things. First, ABM can capture high levels of *heterogeneity*. This is perhaps the best selling point of ABM. By explicitly modelling each and every individual agent that populates the model system, ABMs can cater for the entire spectrum of population heterogeneity, from the most homogenous to the most heterogenous population wherein no agent is alike. This is particularly useful in policy assessment, as a system made up of heterogeneous agents mirrors reality more than a model comprised of a representative agent and thus would predict the impacts of policy better. More importantly, a model of heterogeneous agents can also reflect the distributional aspect of these impacts, which is, or should be, of utmost importance to policymakers. Using an ABM, Lloyd & Chalabi (2021) find that under high climate change, policies that support a market-dependent agricultural development pathway would result in less food availability and higher, more volatile prices in the long run, which in turn would lead to undernutrition in subsistence farmers. Any policies that disadvantage the most vulnerable members of society or discriminate by gender are undesirable regardless of its average impact and should be carefully considered. ABMs enable policymakers to identify such policies.

Second, ABM can allow for *unintended consequences*. Following the idea of emergence, ABM does not assume any axioms, equilibria, or top-down theories. It lets agents act and adapt their actions to past experience and changes in time and space within the confines of simple rules. After the initialisation phase, an ABM lets the model system evolve in response to its micro mechanisms without coming up against theoretical constraints. Researchers simply sit back and watch the model unfold. Accordingly, ABM not only is conducive to generate the unintended but also induces researchers to expect the unexpected. Happe, Schnicke, Sahrbacher, & Kellermann (2009) identify that structural change is an emergent phenomenon and seek to emulate it in their ABM. They discover that in the case of Slovakia, the number of single-holder farms may decrease fast after a certain point in the long-run in response to the Single area payment scheme, contrary to what policymakers may think. Of course, this does not imply that ABMs can predict all unintended consequences. What ABMs can do is acknowledge the uncertainty, the unpredictability inherent in emergence and provide a framework that can accommodate the possibility of unintended consequences.

3.4.2 Agent-centric framework

It might appear tautologic to say that ABM has an agent-centric framework. However, there is a subtle difference between what we mean by agent-based and what we mean by agent-centric. A model is agent-based when it is made up of agents. A framework is agent-centric, to borrow the term from Wilensky & Rand (2015), when it views the components as agents or agent-like entities that receive and deliberate external inputs before acting according to their internal make-up.

As described above, an ABM has three components: agents, space, and time. *Agents* in ABMs are movable entities with four particular properties:

- Agents have *states*: A parlance from computer science, a state of an agent is a set of variables that makes up its attributes and can vary over time. An agent's state influences its actions, so the range of possible actions corresponds with the range of state variables, which is entirely determined by the researchers.
- Agents are *discrete*: There is a clear demarcation amongst agents. It is easy to differentiate between elements of the model that belong and elements that do not belong to an agent.
- Agents are *autonomous* (Wilensky & Rand, 2015): Each agent is independent from other agents and from the environment. Given the stimuli, an agent evaluates its situations and act individually without the need for interventions from other agents. It is in control of its behaviours to the extent that its set of rules permits it.
- Agents are *decisive*: Agents make decisions without fail. Along with their set of attributes, agents are equipped with two other sets of elements which together form their decision-making mechanisms (Bandini, Manzoni, & Vizzari, 2009). One is a set of actions. This is the basis of agent interactions: through actions, agents affect other agents and the environment. The other is a set of rules that controls how actions are selected. To borrow from computer science, this inner structure is termed *architecture* and categorised into *reactive*, *cognitive*, and *hybrid* (Bandini et al., 2009). While cognitive architecture is more sophisticated, each and any of these architectures let agents take in external stimuli, evaluate them, and make decisions regarding how to act based on stimuli perceptions only (reactive), or on a combination of stimuli perceptions and the agents' own states (which also includes memories, knowledge, wants, goals, and expectations) (cognitive).

Space is the environment wherein agents find themselves. In many ABMs, space is normally broken down into discrete plots, patches, or parcels, a legacy from the cellular automata approach. These plots have their own sets of attributes and actions, making them immobile reactive agents. The spaces they form is discrete, but they can also approximate continuous spaces when implemented at a very fine resolution (Wilensky & Rand, 2015).

Space can also be network-based that moves beyond physical and geographical boundaries. This kind of space is referred to as interaction space and represented by nodes and links, which denotes agents and the relationships between two agents respectively. Links are also considered reactive agents in several ABM platforms (Wilensky & Rand, 2015).

More and more ABMs, primarily those in ecology or agriculture or network science, bring space out of the ABM platform. Space is then constructed by external frameworks such as Geographic Information System for geographic space, or Social Network Analysis for network space.

Like other models, ABM also simplifies *time*. In reality, events (which include changes made to space, agents' actions, and the subsequent results) can unfold continually and/or simultaneously. However, in ABMs, events happen sequentially. The order of events is decided by the researchers and can be of considerable importance. Most ABMs model discrete time, i.e. time is divided into discrete intervals of the same length. It is assumed that all events in the model happen once per time interval and happen in every time interval until the simulation terminates (Railsback & Grimm, 2019). Discrete time modelling has three main challenges: how to correctly decide the sequence of events in a time interval, how to determine precisely the length of the time intervals, and how to handle multiple sequences of events during one time interval (Willekens, 2009).

When events are not assumed to happen regularly at every interval of time, ABM can model continuous time. There is no integer time intervals, and events are scheduled to happen at any point in time. In this sense, continuous time modelling can be viewed as splitting time into discrete occurrences of events instead of discrete time intervals. Continuous time modelling is closer to reality and can overcome the challenges of discrete time modelling (Railsback & Grimm, 2019; Willekens, 2009).

The most notable thing about the agent-centric framework of ABM is how the framework, staying true to the bottom-up philosophy, deconstructs its three main components into the most basic units that are conceptually vacant and can be customised to represent anything. This approach affords researchers considerable *flexibility*. For example, researchers can add more agents to a model or take them out with incredible ease since agents are discrete, which means changes made to one agent can be defined so that they do not interfere with other agents. They can calibrate the environment, creating watercourses and land in the same spatial context by setting different attributes for different plots, turning discrete space into continuous space by increasing the number of plots per simulated square meter. They can experiment with different levels of aggregation in their models, from disaggregated individual agents to sub-groups of agents to an entire aggregated system if they so choose. They can too have different combinations of components, such as continuous space and discrete time, or discrete space and discrete time. There are few constraints on how researchers can configure their models.

The agent-centric framework of ABM also facilitates *modularity*. A modular approach to modelling ensures that components can be added, substituted, and updated with ease (Jones, Keating, & Porter, 2001). Modularity is much desirable in agricultural and climate change policy assessment, because (i) it enables fast data and even structural updates, which is crucial as science moves fast and climate change much faster, (ii) it lets researchers from different disciplines develop modules without being weighed down by responsibility towards other modules which do not belong to their expertise, hence encouraging cooperation and knowledge sharing.

ABM, with its flexibility and its discrete, self-contained building blocks, is conducive to modularity. Researchers working in agriculture and ecology have been using ABM to build modular models ever since the methodology's nascence. Berger's (2001) MAS-CA is made up of two sub-models, an economic one and a hydrologic one, linked by a spatial framework. MAS-CA's successor MP-MAS couples decision models with two bio-economic models that can be combined together or used separately as well as a range of optional modules such as out-migration, expenditure, and population growth (Schreinemachers & Berger, 2011). Similarly, the VMD's own integrated land-use change model pushes the three concepts of agent-centric framework, flexibility, and modularity to their natural conclusion and proposes the idea of "co-modelling" architecture or sub-models as discrete, substitutable agents (Drogoul, Huynh, & Truong, 2016). With the delegation of space to external frameworks and platforms, the strengths of modularity are further enhanced.

3.4.3 Simulation capability

The main purpose of simulation models is to reproduce the workings of a system. Depending on the simulation technology, a model can simulate a system either via emulation (i.e. imitating mechanisms) or evaluation (i.e finding numerical expressions for relevant properties). ABMs often have both emulative and evaluative elements: the overall structure of an ABM seeks to imitate the behaviours of individuals that make up the system, and these behaviours are often based on the evaluation of equations which are developed from observed properties (Van Dyke Parunak, Savit, & Riolo, 1998). ABMs therefore have a powerful simulation capability that enables researchers to explore complex systems in richer detail and with a deeper understanding.

By emulating systems from the bottom up, ABM can attend to more systems, assumptions, and scenarios than many other modelling methodologies in three ways. First, ABM can represent systems whose aggregate phenomena are not known or unclear (Wilensky & Rand, 2015). Any top-down modelling approach would require a good understanding of the dynamics at the system level as the basis for the researchers to work their way down. ABM does away with that requirement. All the methodology needs is knowledge of agents' simple, sensible behaviours.

Second, ABM can test assumptions that are mathematically intractable (Crooks & Heppenstall, 2012). Differential equations commonly used in equation-based models can grow exponentially difficult as the interactions they are trying to encapsulate grow more complex, so attempts to describe complex systems using differential equations can become impossible to manage very quickly. Aggregate differential equations also present dynamics in terms of averages, which means they smooth out fluctuations. In cases where the systems being simulated are stable but prone to perturbations, differential equations would not be able to accurately evaluate them. On the other hand, in ABM, equations are most often used as behavioural rules and therefore remain simple even when the interactions between agents become more complex. And as ABM's agents are fundamentally discrete, they are able to reflect well local fluctuations.

Third, ABM's flexibility and modularity make it easier for researchers to examine new scenarios. New combinations of agent attributes can be updated quickly, new interventions included as adds-on with minimal effort, new phenomena modelled without having to first find their equational equivalents, some of which might be difficult to obtain (Reiss, 2011). This encourages more liberal experimentation with the models and allows researchers to expand their sets of possibilities. Emulation can also build scenarios in which all parameters (other than those of interest) can be controlled for so that the differences between the scenarios are reduced to the parameters of interest only. This is useful in ex-ante policy assessment, as researchers can study the effects of different policy interventions in isolation (Thomas Berger & Troost, 2014).

The information that ABM provides for each system, assumption, and scenario is also more comprehensive than other methodologies in three respects (Wilensky & Rand, 2015). First, ABM is able to produce analyses on different levels. Top-down modelling approaches like equation-based or system dynamics modelling deal with system level analysis only. In contrast, ABM tracks each and every individual agent in the system and thus is able to provide a complete history of any agent or zoom out and observe the emerged aggregate results (Wilensky & Rand, 2015).

Second, ABM is able to produce detailed spatial analyses. This is possible because in ABMs, space is made up of reactive heterogenous agents, each with its full sets of attributes. The interactions between agent and space are akin to those amongst agents and therefore can be as complex as required. ABM can therefore generate spatially distributed results as opposed to the averages of spatially independent models (Wilensky & Rand, 2015). This is of particular importance for agricultural development and adaptation to climate change, given that geographic space is a crucial factor of production in agriculture.

Finally, ABM is able to produce detailed temporal analyses. As discussed above, in ABMs events happen sequentially. Thus using ABM researchers can explore more than just a static end state. With access to a detailed account of how the dynamics of the model system transpire in time (Wilensky & Rand, 2015), they can explore causal processes and track feedback loops better than with other modelling methodologies.

3.5 Limitations of ABM

In many aspects ABM certainly has an edge over other methods of modelling, but on a regular basis critics have been vocal about a long list of what they consider drawbacks of ABM. However, we do not consider all of them valid. In our opinion, two of the most common and most undue criticisms of ABM are that (i) ABM is conceptually lesser than other methodologies as it is fundamentally ad hoc and/or has weak theoretical foundation—an assertion repudiated in Leombruni & Richiardi (2005) and further addressed in Berger & Troost (2014)—and (ii) that ABM's generous use of free parameters is a sign of underidentification and can lead to unfounded results—an issue debated in Wilensky & Rand (2015) and Leombruni & Richiardi (2005). On the whole, these and many other criticisms are often a result of (i) a misunderstanding of the nature of ABM, (ii) a misunderstanding of the nature of other modelling methodologies, (iii) an overestimation of the capability of other modelling methodologies in solving common problems that plague modelling in general, and (iv) an underestimation of ABM's capability in providing solutions for the same problems.

Apart from the undue criticisms, ABM does have limitations. Many of the limitations stem from the very root of ABM's key advantage: the ability to capture complexity. The more complex ABMs become, the more walls they encounter with regards to operation and analysis. We identify three such walls in this section. First, ABMs can be computationally demanding. As agents increase in both quantity and quality, they demand more and more computing power to simulate, which in turn extends runtime and makes scalability an issue. For heavyweight models, computing can quickly become expensive and time-consuming even with current developments in computer technology. Confronting this limitation, Wilensky and Rand (2015) argue that a well-designed ABM can save on computing power by "black-boxing" unnecessary parts of the model. Only when there is a need for higher fidelity to reality should the black box be opened. This is evidently an ad hoc band-aid and not a permanent solution, and as the authors themselves concede, high computational expense is the price to be paid for individual-level data. Whether this is a fair price depends on the priorities of the researchers.

Second, ABMs, especially the more complex ones, can be difficult to analyse. A large amount of information coded in an ABM can generate a massive number of processes, which makes it hard for researchers to keep track of and attain a comprehensive understanding of all the interactions, causal links, and feedback effects that have taken place during the simulation period (Manzo & Matthews, 2014). An incomplete grasp of the workings of the model makes the results less transparent at best and at risk of erroneous interpretations at worst, the latter of which is undesirable in policy assessment. Furthermore, if the researchers do not possess ex ante information or a priori theory about the system, they can be at a lost as to the trajectory of the model (Happe & Balmann, 2007). This negates one of the advantages of ABM: that it does not require system-level knowledge to build individual-based mechanisms, illustrating that there is a limit to how complex a model can get before the researchers have to forego certain benefits afforded to them, and researchers have to weigh the trade-offs between additional complexity and other advantages. Nonetheless, there are tools that can help researchers develop a better understanding of unavoidably complex models, such as sensitivity analysis, mathematical analysis using differential equation models (Huet & Deffuant, 2008) or Markov chains (Izquierdo, Izquierdo, Galán, & Santos, 2017) or further computer simulation (Izquierdo et al., 2017).

Third, ABMs are hard to verify and validate. Verification is the process of testing an implemented model for syntactic or logical errors to make sure that the model matches the researchers' conceptual model. Validation is the process of testing to see if the model, both the implemented and the conceptual versions, matches reality. Verifying an ABM is generally more difficult than verifying a mathematical or analytical model. This is particularly true for researchers who are not well-versed in computer programming, as most simulations are implemented using dedicated platforms or programming languages. Validating an ABM is also complicated, since statistical assumptions normally required for validating analytical models such as normality and linearity can be incompatible with the complexity and non-linearity of the ABM (Parker et al., 2003). Moreover, as ABMs in economics and policy assessment are composed of human interactions whose outcomes are difficult to measure and quantify both in simulation and in reality, validating them is a conceptually challenging task.

It is even more arduous to verify and validate highly complex ABMs. The rich sets of agent attributes and the ability to produce emergent outcomes mean that there are innumerable combinations of attributes and model trajectories, some of which have never been considered by the researchers and can lead to flawed results. It is therefore almost impossible to completely verify models of complex systems (Kelton, Sadowski, & Zupick, 2015). Complex ABMs are hard to validate for similar reasons. Unexpected consequences are the norm in ABM, so no surprising results can be treated as outliers and all outcomes must be validated (Manzo & Matthews, 2014). This can quickly become overwhelming with complex models. Unfortunatley, any models that are not adequately validated against empirical data would carry no explanatory weight, which is the case often raised against ABM and simulation in general (Grüne-Yanoff, 2009). However, despite the mounting challenges, the verification and validation of ABMs are topics of interest for many researchers, and innovations have been and continue to be developed to strengthen the empirical capability of ABM (see for instance Macal and North, 2005 for a innovative validation framework and process for EMCAS, an ABM designed to assess policy interventions in the electricity market, Galán et al., 2009 for a design-implementation-verification framework for Pampas, an ABM of agriculture production systems, and Bert, Rovere, Macal, North, and Podestá, 2014 for a validation procedure which includes both qualitative and empirical validation). While there is still no standardised framework to verify and validate ABM, there are procedures and techniques available that could help researchers test and prove the effectiveness of their models.

3.6 Summary

Researchers, not least those working in agricultural economics, have been looking for more suitable models that can help them navigate the increasingly complex juncture of the human and the environmental systems. Out of many new and improved methodologies, ABM stands out as the top candidate. An offspring of complexity theory, ABM takes a bottom-up approach that reads complexity as a consequence of simplicity, treats macro patterns as a manifestation of micro interactions, and seeks to study the whole by manipulating the parts. ABMs make room for heterogeneity, unintended consequences, modularity, and simulation via emulation. Thus, ABM is theoretically poised to tackle complex systems like agricultural economies.

For all its virtues, ABM has its limitations. Considering that ABMs input and output a large quantity of data, they are hugely demanding in terms of data processing and analytical power, which makes them hard to make sense of and gruelling to manage. ABM researchers, tempted by the promise of complexity at their fingertips, may quickly find themselves bogged down with too many assumptions and details they risk misinterpreting. The lack of a standardised toolkit to verify procedures and validate results, a problem too common for methodologies with just a foot in the door, also opens ABM to scepticism and threatens to render its models nothing more than thought experiments coded in computer software with little explanatory power and limited practical application.

Nevertheless, interested researchers need not feel daunted. ABM's advantages offer benefits that are worth proper consideration even in the light of its limitations. If anything, the challenges that come with using ABM keep researchers on their toes, make certain that they continually question their postulations and justify their assumptions theoretically and/or empirically, and help them find as well as push the boundaries of their disciplines. Moreover, like any developing field, ABM is still evolving, and new developments should encourage researchers to explore its possibilities.

With this in mind, we propose in the next chapter an ABM that simulates the agricultural economy of Soc Trang Province in the VMD, and apply it to investigate the impact of a policy regime switch in the context of worsening saltwater intrusion.

Chapter 4

An agent-based model to investigate the impact of a policy regime switch in the Vietnamese Mekong Delta

4.1 Introduction

We present in this chapter an ABM that simulates the economic landscape of Soc Trang Province in the VMD. This model is built by integrating three submodels: the saltwater intrusion model, the economic model, and the behavioural model. The interactions between the submodels and between the elements within each submodel are the basis from which patterns of economic behaviours and land-use decisions arise. We then use this model to assess the impact of a switch away from the Vietnamese government's rice-first agenda on (i) the environment, (ii) the economic interest of farmers in the region, as well as (iii) on food security.

We begin the chapter by formalising the research question, introducing the study area, and summarising the rice-first agenda. Next, we describe the model in detail and outline the course of model analysis. We conclude by setting up scenarios to answer our research question.

4.2 Research question: Agriculture development in the face of climate change

4.2.1 Background and objectives

The VMD is at a crossroads. For the past 40 years, the VMD has grown from one of the most impoverished, famished regions in Vietnam to the country's "food bowl" and one of the top producers and exporters of agriculture and aquaculture products, notably rice, catfish, and shrimp. The relatively fast development pace is due to the opening up of the economy in the 1980s and 1990s, as well as a committed focus on the part of the government on establishing rice production as the regional leading industry, fuelled by concerns for food security and the rising status of Vietnam as a major rice exporter. This has translated into a rice-first agenda, which includes a range of structural and non-structural measures that aim to promote rice production.

However, as one of the world's lowest deltas, the VMD is extremely vulnerable to climate change and its consequences. The intensification of agriculture and related hydraulic infrastructure in the name of development have further exacerbated this problem. The average temperature of the region has increased steadily over the years, threatening to upend the rich ecosystem and biodiversity there. The past decade has witnessed an intensification of natural phenomena common to the region such as flooding, saltwater intrusion, drought, and tropical storms. Extreme natural events have started to occur and with growing frequency. This intensification has reduced agricultural productivity and jeopardised the livelihoods of the majority of the population and especially of rice farmers, whose products are highly sensitive to changes in the environment. At the extreme end of this process are several severe natural disasters that caused significant economic and human losses (see Section 2.3).

To cope with climate change and to get out of a less profitable market, many rice farmers in the VMD are turning towards other agriculture and aquaculture products. In particular, shrimp have been a popular choice. Their high market value and brackish nature make them a seemingly suitable climate change adaptation option for farmers facing a shortage of freshwater to cultivate rice due to drought and saltwater intrusion. However, there are two complications at play. First, permanent shrimp farms are not environmental friendly. They have high carbon footprint and negative effects on their surroundings (see Section 2.2.3.3 and (Kruse et al., 2020; Thu & Populus, 2007; Tien et al., 2019; Veettil et al., 2019)). The expansion and intensification of shrimp production might not be sustainable and can pose even greater environmental and economic risks for the VMD. The less environmentally taxing option of alternating between rice and shrimp is neither popular among farmers nor long-lasting, since it is economically more costly than the permanent rice system but less profitable than the permanent shrimp system (H. D. Dang, 2020; Glassi, Paris, & Truong, 2017; Kien et al., 2020)

Second, the government's rice-first agenda remains in place. Driven still by the need to ensure domestic food security, to maintain the country's position as the top rice exporter in the world, and to appease an entrenched export value chain with various stakeholders including several state-owned enterprises, the Vietnamese government retains many of their measures aimed to urge rice production in the VMD while outwardly and nationally acknowledging the necessity of agricultural diversification when confronted with climate change. Farmers therefore are less incentivised to pursue alternative practices and more encouraged to stick to rice production—the traditional, familiar, but declining livelihood—than they could have been otherwise.

Consequently, the VMD has a decision to make. On one hand, there have been calls for the government to relax or outright abandon their rice-first agenda, citing steep environmental cost and unsustainability as the imperatives (see D. Brown, 2020; Perlez, 2016;

Tatarski, 2021). On the other hand, there is apprehension about a collective, spontaneous, and unorganised switch to other alternative livelihoods, especially shrimp cultivation given its popularity and environmental impacts, that may arise if the government does leave behind their predilection for rice. There is also the issue of economic development to consider, seeing that the delta's population is still much worse off than their industrial and service-based neighbours. As climate change worsens every year, it is necessary for the VMD to strike a balance between economic development and environmental conservation all the while rising to the challenges that climate change presents.

That there are many factors and stakeholders involved compounds the uncertainty and complicates the situation. Issues in policy formulation and implementation also threatens to lead policymakers and farmers astray. This is in no small part the result of (i) the endemic lack of coordination and cooperation amongst sectors and levels of government, which results in hampered information flows and clashing objectives, and (ii) the shortcomings of current policy assessment models, which is partly responsible for the muddled knowledge base about the policy-human-environment nexus in the region (see Chapter 2). The existent knowledge gap of how rice-first measures have impacted farmers (Q. H. Nguyen et al., 2020), especially when taking into account the changing environmental circumstances, makes it much harder for policymakers to formulate a comprehensive development plan that meets the needs, some of which are extremely urgent, of the VMD.

To help address this knowledge gap and facilitate policy formulation, we propose an ABM that can examine concurrently the human-environmental systems in finer detail than what currently used models can offer. As we argue in chapter 3, ABM is the most suitable methodology for our purposes, one that can overcome the drawbacks of other methodologies such as determinism, the aggregate problem, the mono-sectoral and short-term bias, and the top-down approach that leaves uncertainty and unintended consequences unexplored. With its flexibility and modularity, ABM also facilitates quick updates as well as cooperation amongst sectors.

The aim of the model is to investigate the impact of a policy regime switch on the livelihood choices of farmers in the context of climate change. Specifically, the model considers how a switch away from the non-structural measures of the rice-first agenda would affect farmers' land-use choices in the Soc Trang Province, one of the 13 provinces in the VMD, taking heed of the worsening saltwater intrusion. To the best of our knowledge, this is the first model with this aim. There are many policy assessment models applied to the VMD, but most of them study structural measures such as the construction of a high-dyke ring (see Danh and Khai, 2014; D. D. Tran, van Halsema, Hellegers, Hoang, and Ludwig, 2019) or sluice gates management (Baran et al., 2006; Baran et al., 2010). Chapman and Darby, 2016 study both non-structural (alternative rice cropping patterns) and structural measures (strategic flooding) using system dynamics modelling, which is still susceptible to many of the drawbacks listed above (see chapter 3). There are many ABMs applied to Vietnam (for example Castella et al., 2005; D. V. Quang, Schreinemachers, and Berger, 2014), several of which are set in the VMD (Drogoul et al., 2016; Joffre et al., 2015; Smajgl, Toan, et al., 2015). Joffre et al.'s 2015 ABM does consider climate change but only in respect of shrimp aquaculture. Smajgl et al. (2015) and Drogoul et al. (2016) study the human-environmental systems coupled with behavioural mechanisms, but neither of these studies apply their models to policy assessment.

Therefore, with this model, we would like to accomplish the following tasks:

1. To demonstrate the strengths of ABM as a policy assessment tool by developing and applying a model to assess current policy interventions in the VMD as proof of concept.
2. To investigate the impact of the rice-first agenda on the livelihood decisions of farmers facing saltwater intrusion and, in turn, on the environment, the economic interest of farmers, as well as on food security.

4.2.2 Study area: Soc Trang Province

Soc Trang Province is an area of 331,118 ha situated in the southeast of the VMD, at the south estuary of the Hau River, where the river flows into the South China Sea (D. S. Dao, 2018). It is the 6th largest and the 6th most populated province out of the 13 provinces in the region. It has a coastline of more than 72 km and exhibits the typical natural and socio-economic characteristics of the VMD in general and of the Southern coastal area in particular (D. S. Dao, 2018; Ha et al., 2018).

Topology wise, Soc Trang Province is low, flat, and shaped like a basin, which gives the land its distinct gradient along an east-west direction. The easternmost part of the province is the highest with an absolute elevation of about 1.5 m, whereas the westernmost part is the lowest with an absolute elevation of 0.4 m. Relatively high sand dunes alternates with low-lying areas that have high levels of salinity and acid sulphate. The combination of low topology, long coastlines, and extensive canal networks makes Soc Trang Province highly vulnerable to saltwater intrusion (Ha et al., 2018).

Like the rest of the VMD, Soc Trang Province is of tropical monsoon climate with two distinct seasons: a dry season which begins from late November to April and a rainy season which lasts from May to October. The province has a mean annual temperature of 26.8°C and is less prone to tropical storms than other provinces. The mean rainfall is 1,800 mm, and the mean humidity is 83%. Rain is most heavy in August, September, and October, ideal for the SA and AW rice seasons.

Agriculture and aquaculture are the main economic sectors of Soc Trang Province. Rice is the primary product, with annual yield hovering around 6 tonnes/ha (the 4th highest in the VMD) and annual production around 2 million tonnes (D. S. Dao, 2018, GSO, 2020). Shrimp production is the fastest growing economic activity in the past decade, but it is also a risky one, easily affected by diseases and other external factors (D. S. Dao, 2018). Annual shrimp production in the province varies considerable, ranging from 50 to 60 thousand tonnes (GSO, 2020).

The monthly average income per capita in Soc Trang Province in 2019 is 168 USD, roughly the same as the VMD's average and lower than the country's average. The highest income quintile earned 8.7 times more than the lowest income quintile, a number also roughly the same as the VMD's and lower than the country's. There has been a steep rise in out-migration rate since 2015, culminating in the province losing 15% of its population in 2019.

Soc Trang Province has been one of the most affected provinces during the recent spells of drought and saltwater intrusion. In 2016, 31 thousand ha of agriculture and aquaculture products were damaged by abnormally high level of salinity, of which 24 thousand ha of rice lost more than 30% of their yield. The economic loss was estimated at around 27.5 million USD (at the 2019 exchange rate) (Communist Party of Vietnam Online Newspaper, 2016). During the severe saltwater intrusion of 2019-2020, 4 thousand ha of rice was completely lost and much more was damaged (Public Security News, 2021).

The rural-dwelling, small-holding farmers of Soc Trang Province are struggling with the repercussions of climate change. The livelihood of their forebears is ill-protected from the changes for the worse in their environment, and there is a dire need for adaptation and mitigation strategies supported by the authority to help them improve their circumstances.

4.2.3 Rice-first agenda

The rice-first agenda is the unofficial name given to a range of measures that have been promulgated with the ostensible goal of safeguarding rice production and preserving both the nation's food security and the livelihoods of the VMD farmers (Government of Vietnam, 2009, 2015). These measures are divided into two types: (i) structural measures, which involves the construction and operation of hydraulic infrastructure that keeps out saltwater and ensure a constant supply of freshwater, (ii) non-structural measures, which involves direct interventions in both input and output markets, financial incentives in the form of direct subsidies to encourage certain farming practices, and land-use planning.

In our model we focus on non-structural measures, which have hitherto been overlooked in the literature. Structural measures, whose socio-economic impacts are delivered via changes made to the environment, are also implicitly included as part of the saltwater intrusion model. Specifically, we study three policies:

4.2.3.1 Land-use planning

The national government is in charge of agricultural land-use planning at all levels. Resolution No. 63/NQ-CP of the government on National food security in 2009 sets the target of preserving 3.8 million ha of rice paddies by 2020, accounting for 16% of the country's total agricultural land (Government of Vietnam, 2009). Decree No. 35/2015/ND-CP in 2015 sets an upper limit of 20% of total land on the areas of shrimp ponds in the rice-shrimp farming system (Government of Vietnam, 2015). The land-use plan of MARD dictates that 52% of the regions' 3.25 million ha of agricultural land is reserved for rice production and 16% for aqua-cultural production (MARD, 2014). Resolution No.108/NQ-CP of the government decrees that by 2020 at least 42% of land in Soc Trang Province must be used or intend to be used for rice production. Any request for land-use conversion from rice to aquacultural or non-agricultural purposes will either be denied or incur a high conversion fee (GVN, 2015). Any unauthorised conversion will incur a high penalty from 95 USD to 24,000 USD (GVN, 2019).

4.2.3.2 Direct payment

To promote the maintenance of rice paddies as well as the conversion of other types of land use to rice production, the government has been providing direct payment to current and future rice farmers since 2012 (Organisation for Economic Co-operation and Development (OECD), 2020). Current rice farmers receive USD 47/ha of wet rice/year and USD 27/ha of other rice/year, while prospective rice farmers receive 240 USD at the period wherein they make the switch (GVN, 2015).

4.2.3.3 Price support

Resolution No. 63/NQ-CP also sets the goal of ensuring a 30% profit margin for rice farmers by establishing a price floor, also referred to as directed rice price in Decree No. 109/2010/ND-CP. (Government of Vietnam, 2009, 2010). While Resolution No. 63/NQ-CP does not lay down explicitly the means to this goal, the government has employed several tactics such as subsidising domestic institutional buyers or temporarily expanding the buffer stock (VOV-ĐBSCL Journalists, 2019). Decree No. 109/2010/ND-CP also states that if the market price is higher than the price floor, the government would not intervene.

4.3 Model description

In this section, we describe our model following the ODD (overview, design concepts, and details) protocol developed by Grimm et al., 2020 in the interest of consistency and clarity. The model is implemented in NetLogo, a programming language and integrated development environment designed specifically for ABM.

4.3.1 Purpose and patterns

4.3.1.1 Purpose

To achieve the overall objectives laid out in Section 4.2.1, our model aims to understand how three specified policies influence the land-use options of farm agents and consequently the total production of key crops rice and shrimp, their prices, the profit of farm agents, and soil salinity in the region. Specifically, what we expect from the model is a qualitative inspection of the impacts, which includes their patterns, directions, and relative sizes. Two main elements drive the model: the human-environment interactions and the decision-making mechanism of farm agents.

4.3.1.2 Patterns

There are two patterns the model is expected to reproduce:

1. **Response of farmers to saltwater intrusion:** As saltwater intrudes further inland, rice—a freshwater crop—becomes a suboptimal choice for farmers in high saline areas. As a result, farmers switch en masse to shrimp farming. This is a land-use pattern well observed in the VMD (Liu et al., 2020).
2. **Alternating farming system as a temporary choice**: The alternating rice-shrimp farming system is not a permanent choice for the majority of farmers as it i) has a lower benefit-cost ratio than both the permanent rice and the permanent shrimp systems due to the high cost of material input for shrimp production but low revenue from rice production (Glassi et al., 2017) ii) is less efficient than the permanent shrimp system, causing low shrimp production (Kien et al., 2020). Therefore farmers switching to the alternating rice-shrimp system will shortly switch back to either of the permanent systems.

4.3.2 Entities, state variables, and scales

Within the NetLogo environment, agents are divided into four types: turtles, patches, links and the observer. We use three of them to represent three entities in our model: (i) turtles representing farmers, which is our shorthand for farm entities that include a farm manager, usually the household head, and family members, (ii) patches representing individual plots of agricultural land, and (iii) the observer representing an overseer that controls global variables.

4.3.2.1 Land

In the model, the simulated NetLogo "world" consists of $39 \times 39 = 1,521$ patches. The easternmost 39 patches represent the open sea—the primary source of salinity. The northernmost 38 patches represent the Hau River, which is situated to the northwest of Soc Trang Province. With the dense network of irrigation canals taking water from the Hau River, the salinitisation of this river owing to rising sea level would also aggravate the salinity intrusion. Each of the other 1,444 patches represents a plot of agricultural land 10 m x 10 m in size. The total area is 1,444 ha and is equivalent to approximately 1/200 of the actual area of Soc Trang Province's agricultural land.

Aside from type (sea, river, and land), land patches have five other attributes: tenure, location, use, salinity level, and crop productivity levels, and location. The tenure attribute identifies the owner of each plot of land. It is represented by a variable carrying the ID numbers of the farm agents to whom the plot belongs. The location attribute includes two variables that measure the distances from the plots to the sea and the river. These variables are used to compute the salinity level of the plots (see 4.3.7.1).

Land use reflects the farm agents' choices of farming system: permanent rice, alternating rice-shrimp, and permanent shrimp. Along with land use, salinity level is one of the key components of the model mechanisms. The salinity level of seawater is set at 55 dS/m (Queensland Government, 2018). The salinity levels of both the Hau River and the soil are subsequently set based on the salinity level of seawater and the saltwater intrusion rates, which will be discussed in further detail in Section 4.3.7.1 on the saltwater intrusion model.

The salinity level of each plot of land is translated into its crop productivity levels by the crop production functions (see Section 4.3.7.2). Crop productivity levels determine the annual yield of each type of crop that the plot of land can produce. The model represents these levels as simple index values that capture the difference between the productivity levels of the plot and the maximum levels, the latter of which correspond to index values of 1. We assume that the entire area of each plot of land is dedicated to production.

4.3.2.2 Farm agents

Farm agents belong to the turtle class in the NetLogo world. Each farm agent is situated on one plot of land which they also own and operate as a factor of production. Farm agents do not own any other plots. This assumption corresponds to the fact that in the VMD in general, farms are small. The average landholding size of a farm household ranges from approximately 0.8 to 1.3 ha (Glassi et al., 2017; Markussen, 2015; The Anh, Van Tinh, & Ngoc Vang, 2020).

Each farm agent has their own production profile. The production profile consists of farming system and farm size. In the model, there are three farming systems: permanent double-crop rice, alternating rice-shrimp, and permanent double-crop shrimp. These farming systems are chosen because firstly, rice and shrimp are the dominant agricultural products in the province (D. S. Dao, 2018). Secondly, while triple-crop rice is the slightly more popular farming system (Yen, Son, Tung, Amjath-Babu, & Sebastian, 2019), the production of the SA and AW crops are small in comparison to the WS crop and usually combined in data reports (GSO, 2020). Therefore, the model combines the SA and AW crops and considers only the double-crop rice system.

We opt to keep farm agents fairly homogenous in our model. Farm agents share the same demographic attributes (such as age, education levels, gender, etc.), and managerial ability (which is proxied by cost structure, risk preference, and expectation formation coefficients). This is justified by the fact that farmers in the VMD do not differ considerably from one another due to a rich and recent history of collective rice farming. Farm agents are also assumed to have similar financial profiles. This appears to be a less excusable assumption, since there is evidence of economic differentiation amongst farmers in the region. But a closer look at the data reveals that this differentiation arose first between self-sufficient farmers and commercial farmers in the 1990s (T. T. Dao, 2018), then between non-agricultural and agriculture household in the 2000s, and finally as a result of disparities in landholdings, which have emerged after decades of land-use rights privatisation and land market development (Kojin, 2020b). As we do not consider land market in our model, we rationalise our homogeneity assumption by restricting our farm agents to commercial farmers of similar size.

Thus, farm agents only have three types of state variables:

- Variables that belong to the *production profile*, which consists of farming system, total area dedicated to each crop, crop productivity levels which corresponds to those of land, and stochastic elements that representing variations in yield (see Section 4.3.7.2)
- Variables that belong to the *cost structure*, which includes components of variable costs, fixed costs, revenue, profit, price of rice supported by the government, and government transfers (see Section 4.3.7.2)
- Variables that belong to the *decision-making mechanism* which includes among other the expectation weight and land-use choice for the next period (see Section 4.3.7.3)

4.3.2.3 Overseer

The overseer supervises the land and farm agents. This agent is responsible for initialising global variables (see Appendix A for a comprehensive list) and keeping time for the simulation as well as giving instructions to the other two types of agents. In a sense it can be regarded as the model's equivalent to both the government (which administers activities such as setting policies, delivering government transfers, and collecting data) and nature (which controls pertinent processes such as saltwater intrusion).

4.3.2.4 Temporal scale

Each simulation period of the model is equivalent to one calendar year, as the events set out in the submodels (saltwater intrusion, crop production, and land-use decision) generally occur on a yearly basis.

4.3.3 Process overview and scheduling

Figure 4.1 illustrates the procedure of the model during one simulation period. The procedure is carried out by the same actor and in the same order in each period. After the initialisation phase wherein the model agents and the environment are created, the simulation begins with the saltwater intrusion model, which updates the salinity level of the land plots. Severe saltwater intrusion has a p chance of happening.

After the saltwater intrusion model, the economic model is executed. The sequential procedure of this submodel is: crop production, crop marketing, and profit computation. To minimise complexity, we assume that the agricultural product markets are always cleared. This is not too far-fetched an assumption, since the Vietnamese government keep a close eye on the domestic rice market and intervene when necessary (Cramb, 2020).

The behavioural model follows, with the farm agents first being queried to predict future salinity conditions, then analyse potential land use options and select the one with the highest profit.

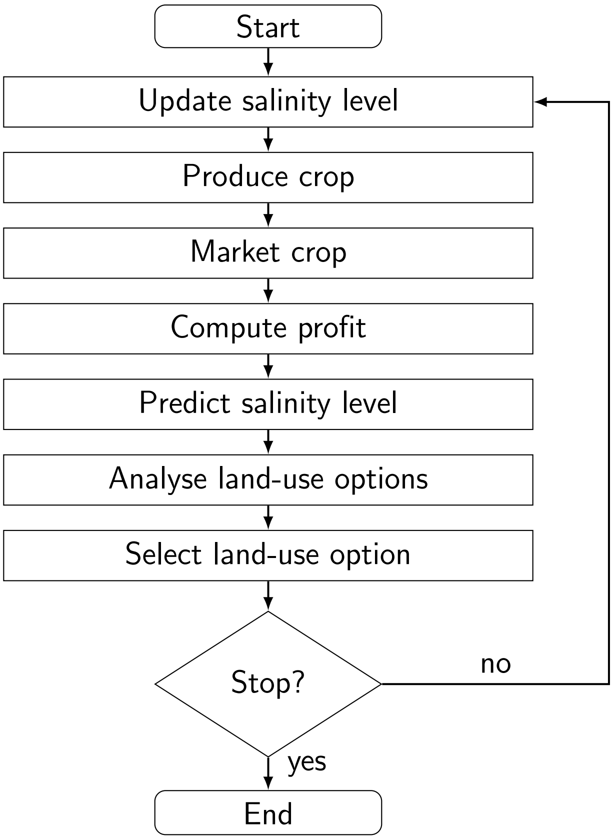


Figure 4.1: Model procedure for each simulation period

4.3.4 Design concepts

4.3.4.1 Basic principles

In our model, farmers are assumed to engage in one main activity: producing and selling farm crops. All the land-use decisions for which farmers are responsible are related to this activity. The foundational assumption of the model is that a farm agent's activities and decisions are constrained by three factors: the financial situation of the farm agent, the environment wherein the farm agent is situated, and the actions of other farm agents within the same environment and geographical area.

The environment is defined here as a collection of attributes that affect the crop production of the farmers. The main focus of our model is the salinity level of the soil, which is partially endogenised via a feedback loop: along with other attributes, the salinity level determines the amount of yield a plot of land is capable of producing, which influences the land-use decisions of the farm agent who owns the plot, which in turn affects the salinity level. The key fact that makes up the conceptual foundation of the model is that different uses of land affect soil salinity differently.

Due to the saltwater intrusion mechanism among contiguous plots, the salinity level of a plot of land not only determines and is determined by the use of the plot itself, but also by the use of other plots. Thus, a farm agent's production capability is constrained not only by their own activities, but also indirectly by the activities of their neighbours. This results in a system of interlocking feedback loops, as shown in Figure 4.2.

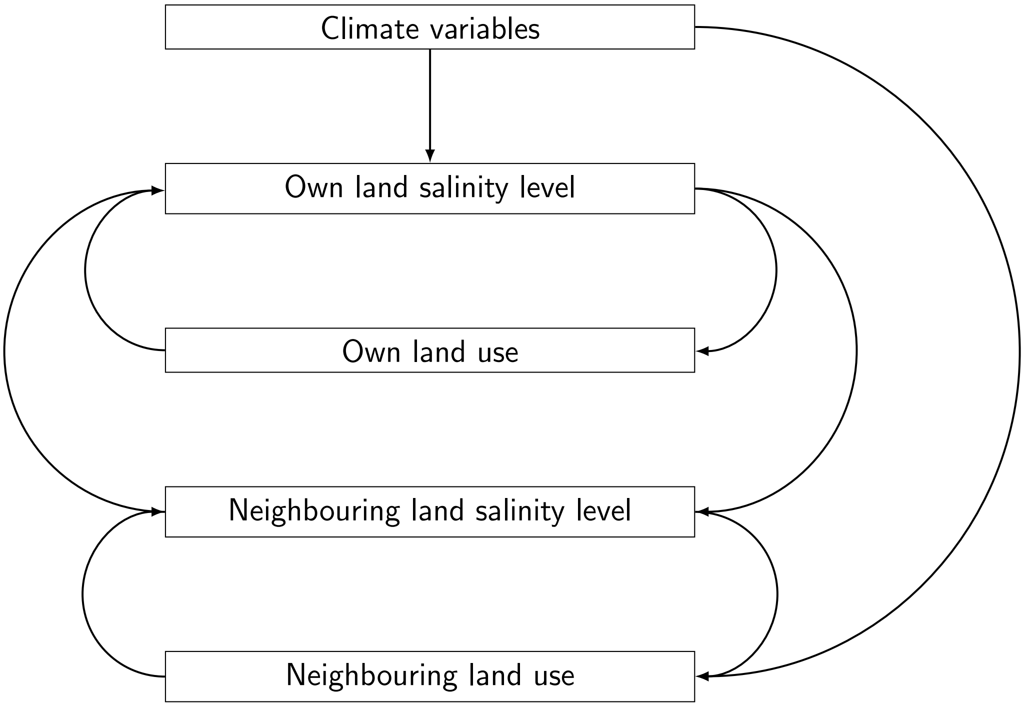


Figure 4.2: Feedback loops of the model

The farm agents in the model are initialised to be homogenous. Demographic, managerial and financial differences (which include differences in expectation formation and risk preference) are not taken into account. In addition, they are considered to have constant crop production technology. These assumptions allow us to isolate the effects of increasing salinity intrusion, and, by extension, of aggravating climate change conditions, on land use from the effects of technological advancement, demographic changes, managerial attributes, and wealth distribution.

4.3.4.2 Emergence

Land-use patterns, livelihood performance, crop supply, and salinity distributions are the primary results of the model. These results emerge from the individual land-use decisions made by farm agents in response to changes in soil salinity caused by natural forces as well as by the choices of other farm agents.

4.3.4.3 Adaptation and objectives

Farm agents have one course of action to adapt to the changing environment: deciding which farming system to implement in the next period. The underlying decision-making mechanism is modelled in the form of direct objective seeking using optimisation: farm agents choose the farming system that generates the most expected profit. In this sense, the farm agents are assumed to behave according to neoclassical economic theory. This assumption is appropriate for the VMD and Soc Trang province, given the commercial nature of the region's agriculture (as opposed to subsistence or extensive agriculture) and that the majority of farmers there live hand-to-mouth. It is also backed by several studies highlighting the importance of economic returns in determining farmers' decisions (R. H. Bosma, Udo, & Verreth, 2005; H. Q. Nguyen et al., 2019; V. H. Tu, Can, Takahashi, Kopp, & Yabe, 2018).

4.3.4.4 Learning

No learning is implemented in the model. The farm agents have only one decision-making mechanism throughout the entire simulation. In other words, they do not change how they make decisions.

4.3.4.5 Prediction

The farm agents choose farming system based on explicit estimations of future profit using a simple adaptive expectations mechanism (see the behavioural submodel in Section 4.3.7.3).

4.3.4.6 Sensing

The farm agents are able to determine the salinity level of their land in the current period with perfect accuracy.

4.3.4.7 Interactions

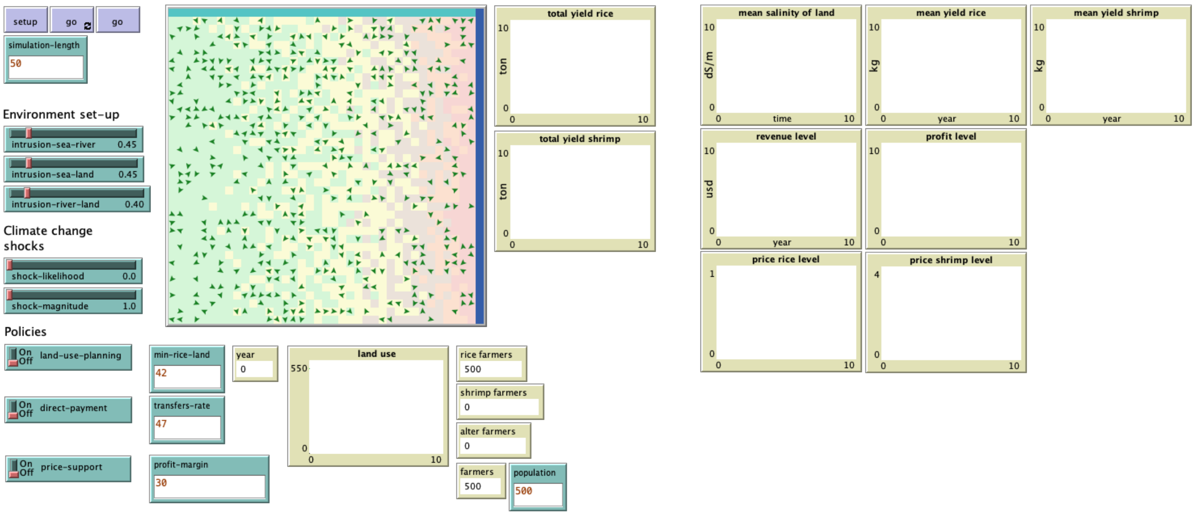
The model implements 3 kinds of interactions: between land and farm agents, among plots of land, and among farm agents. Plots of land interact *directly* with one another via the saltwater diffusion mechanism: saltwater spread from one plot to their neighbours. Land also interacts *directly* with farm agents: farm agents use land to produce crops while the salinity level of land governs farm agents' choices. Farm agents interact *indirectly* with one another. Their interaction is mediated by their land-use decisions: a land-use decision made by one farm agent can cause changes in the decision space of other agents on account of the humans-environment feedback loops in Figure 4.2. All interactions take place at a local level as both land and farm agents are only able to interact with other land and farm agents in their immediate vicinity (in their Moore neighbourhood).

4.3.4.8 Stochasticity

The model has four sources of stochasticity. First, stochasticity is used in the initialisation phase to position newly generated farm agents. Second, stochasticity is used to set the base salinity level of land before saltwater intrusion, which depends solely on land use. Third, stochasticity is also present in determining the timing, the magnitude, and the total number of severe saltwater intrusion events. Finally, stochasticity is implemented in crop production. The production functions have a random variable that incorporates observed variations in yield that can be attributed to factors such as pest or disease risks.

4.3.4.9 Observations

Observations include (i) graphical output showing the salinity levels of individual plots of land as well as land-use patterns (Figure 4.3), (ii) graphs detailing the temporal patterns of land use, livelihood performance, crop prices, and crop production, (ii) summary statistics on the number of farm agents practicing each farming system and their profit rates.



simulation-length 50

Environment set-up

intrusion-sea-river 0.45

intrusion-sea-land 0.45

intrusion-river-land 0.40

Climate change shocks

shock-likelihood 0.0

shock-magnitude 1.0

Policies

On Off land-use-planning

On Off direct-payment

On Off price-support

min-rice-land 42

transfers-rate 47

profit-margin 30

year 0

rice farmers 500

shrimp farmers 0

alter farmers 0

farmers 500

population 500

Figure 4.3: The Graphic User Interface (GUI) of the model implemented in NetLogo

4.3.5 Initialisation

4.3.5.1 Land

At period $t = 0$, the model environment is without previous human influence and consists of $39 \times 39 = 1,521$ patches of $10x10$ metres. The easternmost 39 patches have their type attribute set as "sea", the northernmost 38 patches as "river". The other 1,444 patches are set as "land". The salinity levels of the "sea" patches are set at 55 dS/m (Queensland Government, 2018). The salinity levels of the "river" patches are set based on the salinity levels of the closest "sea" patches and saltwater intrusion rate; the salinity levels of the

Level of salinity (dS/m)	Salinity class
< 2	No salinity
$2 - 4$	Low salinity
$4 - 8$	Medium salinity
$8 - 16$	High salinity
> 16	Very high salinity

Table 4.1: Classification of soil salinity

Source: K. A. Nguyen, Liou, Tran, Hoang, and Nguyen, 2020

"land" patches are set based on the salinity levels of the closest "sea" and "river" patches, the salinity of their neighbouring patches, and two different saltwater intrusion rates, one for saltwater intruding from the river and one for saltwater intruding from the sea. All saltwater intrusion rates are calibrated to achieve a qualitative equivalence of recorded spatial distributions of salinity level along the Hau River at high water slack (from around 16 dS/m at the estuary mouth to < 1 dS/m at 30 km upstream) (N. P. Mai et al., 2020; A. D. Nguyen & Savenije, 2006). Patches are classified based on their salinity levels using the classification table in K. A. Nguyen, Liou, Tran, Hoang, and Nguyen, 2020 (reproduced in Figure 4.1

4.3.5.2 Farm agents

At period $t = 0$, 500 farm agents are generated at random locations. All farm agents are initialised as practicing the permanent double-crop rice farming system. Parameters pertaining to agents' history at $t - 1$ are also set at this stage.

4.3.6 Input data

The cost structure of the farm agents use data from the rice producer survey conducted by (The Anh et al., 2020) and from small group discussions with community leaders of villages in the Soc Trang Province conducted by Glassi et al., 2017.

4.3.7 Submodels

4.3.7.1 Saltwater intrusion model

Every year, saltwater intrudes upon the VMD during the dry season (from November to April). This coincides with the WS rice season, which is the most important season during the agricultural year. The further inland saltwater reaches via river canals and aquifers, the more damage it causes to rice paddies. When the rainy season arrives (from May to October), rainwater and upstream floods replenish the aquifers and flush the saltwater out of the inland. If the rain comes late or the upstream flood is weak, saltwater will linger in the soil and threaten the SA rice season.

The detrimental development of saltwater intrusion observed in the past decade can be directly attributed to two factors: an increase in human activities (such as hydropower plant construction and sand mining) both upstream and downstream and an increase in adverse natural conditions which includes sea level rise and droughts (Jordan et al., 2020; K. A. Nguyen et al., 2020; T. V. Tran et al., 2019; Vu et al., 2018). During the drought of 2016, saltwater intruded 60-65 km along the rivers and 70-85 km inland, 20-30% higher than in previous years (N. P. Mai et al., 2020; C. T. Nguyen, 2016). Almost all of Soc Trang Province was heavily salinised: the communes furthest away from the sea were infected with a salinity concentration of 6-12 dS/m ($\approx 4-8$ m/l)[1] (T. C. Quang, Nghi, & Minh, 2017). In 2020, saltwater intruded 2 km deeper than in 2016, signalling a worsening trend (United Nations Vietnam, 2020).

To simulate the saltwater intrusion, the model relies on three parameters that determine the rates of saltwater intrusion from sea to river via tidal regime, from sea to soil through aquifers, and from river to soil through both the network of canals and the aquifers. At the beginning of each simulation period, the salinity level of each patch of rice land or river is “reset” back to 0 dS/m, which can be interpreted as the flushing process. On the other hand, patches of rice-shrimp and shrimp land have their salinity levels reset at $s \sim N(2, 1^2)$ and $s \sim N(20, 2^2)$ respectively. This is because shrimp ponds accumulate salt in the soil that cannot be completely flushed out, and the more intensive the shrimp ponds are, the higher the salt concentrations become (Kruse et al., 2020).

In reality, freshwater has a salinity level ranging from 0-1.5 dS/m, and the areas by the sea always have brackish water (from 1.5-15 dS/m) even with the flushing process due to the tides constantly bringing in saltwater. In other words, in coastal areas and estuaries, saltwater intrusion can be said to occur all year round, only tempered by freshwater during the rainy season but not fully prevented. The model chooses to bypass this technicality for simplicity’s sake, since the main output of this submodel depends solely on the results of the saltwater intrusion process in the next step, which will also establish the brackish condition of the coastal areas.

In the second step, saltwater intrudes. The river receives salinity from the sea through the saltwater intrusion function:

$$s_{r,l} = \frac{\lambda_{s,r}}{d_s} \times 55 \tag{4.1}$$

where $s_{r,l}$ = salinity level of patch of river l

$\lambda_{s,r}$ = rate of saltwater intrusion from sea to river

d_s = distance to the closest patch of sea

---

[1] Vietnam Disaster Management Authority considers soil with a salinity concentration of 6 dS/m (≈ 4 m/l) as salinity infected

1	2	3
4	i	5
6	7	8

Figure 4.4: A typical patch of land i and its land neighbours

According to this function, the closer a river patch is to the sea, the more salinity it receives.

Subsequently, each patch of land receives salinity from three sources: the closest patch of sea, the closest patch of river, and the neighbouring patches of land. In most cases, a patch of land i has 8 neighbouring land patches (Figure 4.4). Patches at the edge of the NetLogo world or bordering bodies of water have fewer neighbours. The saltwater intrusion function for land is:

$$s_i = \frac{\lambda_{s,l}}{d_{l,s}} \times 55 + \frac{\lambda_{r,l}}{d_{l,r}} * s_{r,i} + \frac{\sum s_j}{\max(j)} \tag{4.2}$$

$$\begin{aligned} \text{where} \quad s_i &= \text{salinity level of patch of land } i \\ \lambda_{s,l} &= \text{rate of saltwater intrusion from sea to land} \\ d_s &= \text{distance between patch of land } i \text{ and the closest patch of sea} \\ \lambda_{r,l} &= \text{rate of saltwater intrusion from river to land} \\ d_r &= \text{distance between patch of land } i \text{ to the closest patch of river} \\ s_{r,i} &= \text{salinity level of the patch of river closest to patch of land } i \\ s_{i'} &= \text{salinity level of the neighbouring patch of land } i',\ i' \in [1, 8] \end{aligned}$$

During each spell of severe saltwater intrusion, all rates of saltwater intrusion λ_{sr}, λ_{sl}, and λ_{rl} increases by N times, with $N = \nu + \epsilon$. ν is referred to in the model as the shock magnitude and ϵ as a stochastic element, $\epsilon \in [0, 2)$. Since severe saltwater intrusion is positively correlated with drought, and extreme spells of drought have a high tendency to coincide with the El Niño-Southern Oscillation periods, severe saltwater intrusion has a $p = 0.3$ chance of happening (based on the number of El Niño periods and corresponding extreme drought events in the VMD from 1985 to 2020 (C. N. Quang, Hoa, Giang, & Hoa, 2021)).

The foremost limitation of this submodel is that it greatly simplifies several natural processes, sacrificing accuracy in return for parsimony. It also makes the assumption that saltwater intrusion, and by extension climate change, does not worsen. Nevertheless, the submodel manages to visually match the maps of salinity at both normal and extreme conditions as well as future projections (Khong, Young, Loch, & Thennakoon, 2018; Minh Tuyet, 2016; T. C. Quang et al., 2017).

4.3.7.2 Economic model

The economic submodel consists of three components: crop production, crop marketing, and profit computation.

Crop production

The only factor of production we consider in our production functions is land. The salinity level of each patch is converted into a yield index that is the relative yields of rice and shrimp written as functions of salinity level[2]:

$$y_{k,i} = 1 - b_k(s_i - a_k) \tag{4.3}$$

where $y_{k,i}$ = relative yield of crop k of patch i (from $0 - 1$)

a_k = the salinity threshold beyond which relative yield of crop k starts to decline (dS/m)

s_i = the salinity level of patch i

b_k = the rate of decline.

If $k = r$ (rice), $a_r = 3$ and $b_r = 0.12$ (Tanji & Kielen, 2002). If $k = s$ (shrimp), $a_s = 46$ and $b_s = 0.1$ (Kiruthika et al., 2013; Soundarapandian & Gunalan, 2008).

The yield index of land is then converted into the productivity index of farm agents by taking the average of the yield indexes of all plots of land that farm agents own. Since each farm agent only owns one plot of land in our model, their productivity indexes are equal to the yield indexes.

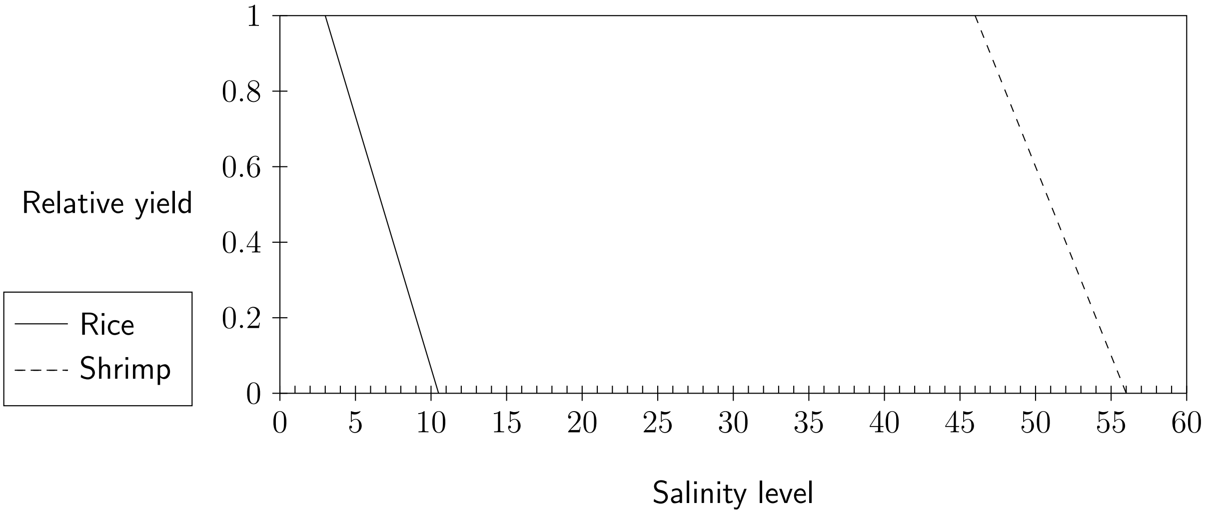


Figure 4.5: Relative yields of rice and shrimp as functions of salinity level

To reflect other exogenous factors such as varied weather patterns, in the model we

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[2] adapted from Maas and Hoffman, 1977

assume a small variation in yield which we refer to as α. α ranges from 0-10% of the mean yield for rice production, and 0-25% for shrimp production.

The amount of rice on a plot of land is determined by the mean yield, which is the same for all farm agents, the productivity index, the total area of land used for rice production (which is the physical area times the number of rice harvests), and the yield variation α:

$$Y_{r,i} = (Y_{\mu r} \cdot \rho_{r,j} - \alpha_r) * A_r \tag{4.4}$$

where $Y_{r,i}$ = total rice yield of patch i
$Y_{\mu,r}$ = mean rice yield
$\rho_{r,j}$ = rice productivity of farm agent j
α_r = rice yield variation
A_r = total area of land used for rice production

In addition to all the above elements, the shrimp production function also admits disease risk δ. δ depends on many factors, but for the purposes of our model, δ is written as a function of shrimp farm density and time. This is because the more shrimp farms operate in an area, the more susceptible to disease the shrimp become (Bhowmick & Crumlish, 2016; Duraiappah, Israngkura, & Sae-hae, 2000).

$$\delta = 2 \cdot \left(\frac{\sum Z_s}{\sum Z}\right) + \left[2 \cdot \left(\frac{\sum Z_s}{\sum Z}\right)^2\right]^{t-1} \cdot 0.1 \tag{4.5}$$

where δ = disease risk of shrimp
$\sum Z_s$ = number of land patches used to cultivate shrimp
$\sum Z$ = number of land patches
t = current period

The shrimp production function therefore is:

$$Y_{s,i} = [Y_{\mu s} \cdot (\rho_{s,j} - \delta) - \alpha_s] * A_s \tag{4.6}$$

where $Y_{s,i}$ = total rice yield of patch i
$Y_{\mu,s}$ = mean rice yield
$\rho_{s,j}$ = rice productivity of farm agent j
δ = disease risk of shirmp
α_s = rice yield variation
A_s = total area of land used for rice production

The total amount of yields a farm agent receives is equal to the sum of the yields harvested from the plots of lands owned by the farm agent:

$$Y_j = \sum_{i \in j} (Y_{r,i} + Y_{s,i}) \tag{4.7}$$

where Y_j = total yields of farm agent j
$Y_{r,i}$ = total rice yield of patch $i$owned by farm agent j
$Y_{s,i}$ = total shrimp yield of patch $i$owned by farm agent j

Crop marketing

The revenue gained from a crop is computed based on the regional crop price. The regional rice price is either the market price or the price floor that ensures at least 30% profit margin for farmers (Government of Vietnam, 2009; OECD, 2020). The regional shrimp price is left largely to the market. Global prices and their variations have no role in this model as well as in reality, given that farmers are at the leftmost of the VMD agricultural value chain and face the regional prices while global prices are the domain of exporters (L. Nguyen, Khoi, Hien, & Phuong, 2019; The Anh et al., 2020).

$$R_j = \sum_{i \in j} (Y_{r,i} \cdot P_r + Y_{s,i} \cdot P_s) \tag{4.8}$$

where R_j = gross revenue of farm agent j
$Y_{r,i}$ = total rice yield of patch $i$owned by farm agent j
P_r = price of rice
$Y_{s,i}$ = total shrimp yield of patch $i$owned by farm agent j
P_s = price of shrimp

The modelled cost structure involves two kinds of cost: fixed costs and variable costs. Fixed costs are composed solely of machinery depreciation costs, which are set exogenously and uniformly across all farm agents and over time as the result of the constant crop production technology assumption. This can be interpreted as farm agents' annual capital investment. Land rent is not included in the model, because land renting is not a prevalent practice in the VMD: T. H. Quang and Nghi, 2016 reports that only 8% of farmers in their survey rented land, Markussen, 2015 observes that the trend has been decreasing, and The Anh et al., 2020 notes that for renting farmers, land rent only accounts for 3% of their total costs.

$$FC_j = D_r + D_s \tag{4.9}$$

where FC_j = fixed costs of farm agent j
D_r = machinery depreciation cost of rice
D_s = machinery depreciation cost of shrimp

Variable costs are composed of input costs and labour costs. Generally, farm labour comes from two sources: members of the farm household, whose wages are implicitly taken from profit, and external workers, whose wages are treated as farming overheads. Our model assumes that farm agents can hire labour on a fixed rate. This assumption is not too far from reality, as Soc Trang Province has a sizeable population of landless ethnic workers that provide seasonal agricultural labour to farms both within and without the province (Tuyen, 2012). As both input and labour costs are dependent on the areas of land cultivated, they are written as functions of total areas of land owned by farm agents. Transportation and transaction costs are omitted to keep the model as simple as possible.

$$\begin{aligned} VC_j &= VC_{r,j} + VC_{s,j} \qquad (4.10)\\ &= \left(\frac{(IC_{r,j} + W_{r,j})}{5} \cdot A_{r,j}\right) + \left(\frac{(IC_{s,j} + W_{s,j})}{5} \cdot A_{s,j}\right) \qquad (4.11)\end{aligned}$$

where VC_j = variable costs of farm agent j
$VC_{r,j}$ = rice variable costs of farm agent j
$IC_{r,j}$ = input costs of farm agent j per ha of rice
$W_{r,j}$ = hired labour costs of farm agent$j$ per ha of rice
$A_{r,j}$ = total area of land used for rice production by farm agent$j$
$VC_{s,j}$ = shrimp variable costs of farm agent j
$IC_{s,j}$ = input costs of farm agent j per ha of shrimp
$W_{s,j}$ = hired labour costs of farm agent$j$ per ha of shrimp
$A_{s,j}$ = total area of land used for shrimp production by farm agent$j$

Input and output markets

We take a leaf out of Balmann's (1997) book and assume that the market prices of input, labour, and crops are determined by price functions of the form:

$$p_{z,t} = p_{z,t-1} \cdot [1 + \theta(x_{z,t} - 1)] \tag{4.12}$$

where $p_{z,t}$ = price of input or output z in period t
$p_{z,t-1}$ = price of input or output z in period $t-1$
θ = coefficient controlling for price variation
$x_{z,t}$ = term allowing for price variation based on the aggregate supply of z at time t

For the input and and hired labour markets, we assume that $\theta = 0$. In other words, we assume that prices[3] remain unchanged over time and irrespective of supply. Admittedly, this is not a realistic assumption, but one that is chosen for its straighforwardness.

For the output, i.e. the agricultural product markets, the price functions are

$$P_{k,t} = P_{k,t-1} \cdot \left[1 + \theta\left(\frac{Y_{k,t-1}}{Y_{k,t}} - 1\right)\right] \tag{4.13}$$

where $P_{k,t}$ = price of crop k in period t
$P_{k,t-1}$ = price of crop k in period $t-1$
θ = coefficient controlling for price variation
$Y_{k,t-1}$ = total yield of crop k in period $t-1$ of all farm agents
$Y_{k,t}$ = total yield of crop k in period t of all farm agents

Profit computation

Basic farm accounting rules are applied to generate farm agents' profit during each simulation period, which is equal to revenue minus costs plus government transfers (if any).

$$\pi_j = R_j - FC_j - VC_j + GT_j \tag{4.14}$$

where π_j = profit of farm agent j
R_j = gross revenue of farm agent j
FC_j = fixed costs of farm agent j
VC_j = variable costs of farm agent j
GT_j = government transfers that farm agent $j receives$

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[3] all prices are real as we do not take into account the nominal side of the economy

4.3.7.3 Behavioural model

The one and only goal of farm agents in our model is to maximise their profit. Therefore, farm agents will make their managerial decisions on the expected income from each of the farming systems available to them, which is the sum of the expected revenue and expected government transfers minus expected costs. The expected government transfers depend on the current policy, while the expected revenue will ultimately depend on the expected relative yield of crops as a function of expected salinity condition. To compute individual farm agents' expectations, we use a simple adaptive expectations mechanism: farm agents revise data from the previous period with data from this period. Thus, the expectations that farm agents form in this period are the weighted averages of present and past data.

$$E[y_{k,i,t+1}] = (1-\omega)\cdot y_{k,i,t-1} + \omega \cdot y_{k,i,t} \tag{4.15}$$

$$E[p_{k,t+1}] = (1-\omega)\cdot p_{k,t-1} + \omega \cdot p_{k,t} \tag{4.16}$$

where $y_{k,i}$ = relative yield of crop k pf patch i
ω = weight of the present information
p_k = price of crop k

The expectation weight ω is set at 0.2, as past climate experience is determined to be the most important determinant of farmers' adaptive choice (Ngo, 2016).

From the expected relative yield of crops as a function of salinity and the expected prices, expected total yields and expected revenues of all three possible options are estimated. Corresponding total costs are also calculated. Expected profit of each option is then equal to expected revenue minus expected costs plus expected government transfers. We assume that farm agents expect no changes to costs or policy throughout the simulation.

Farm agents are asked to choose the farming system that is expected to generate the most profit. If their first choice is not available to them on account of policy constraints (see Section 4.3.7.4), they would move on to the next best choice.

4.3.7.4 Rice-first agenda

Land-use planning

In the model, we assume full enforcement and no unauthorised conversion. A shrimp land quota is calculated according to the minimum amount of rice land to be preserved. During each simulation period, if the number of farm agents that choose to switch to permanent double-crop shrimp farming system exceeds the quota, then the excessive farm agents are not permitted to make the switch.

Direct payment

In the model, all farm agents are assumed to cultivate wet rice. Direct payment for current rice farmers is included in government transfers, while direct payment for prospective rice farmers is not considered.

Price support

To adhere to the spirit of this measure, which is to ensure a minimum profit margin of 30% for farmers, in our model each farm agent has a customised price floor that is wholly dependent on their costs. Since we assume that farm agents have similar cost structures and landholdings, it implies that farm agents will also have the same price floor. This would no longer be the case when the homogeneity assumption is relaxed. In that situation, the individual price floors can be interpreted as payments to producers if needs be.

The price floor of rice is calculated as:

$$P_{r,j} = \frac{(FC_{r,j} + VC_{r,j})}{Y_{r,j}} \cdot 130\% \tag{4.17}$$

where $P_{r,j}$ = price floor of rice of farm agent j
$FC_{r,j}$ = rice fixed costs of farm agent j
$VC_{r,j}$ = variable costs of rice of farm agent j
$Y_{r,j}$ = total rice yield of farm agent j

4.4 Model analysis

4.4.1 Model verification

As straightforward as our model appears to be, the translation from concepts to operating computer codes is not guaranteed to be error-free. Therefore we borrow two verification techniques from software engineering to make sure that our model design is correctly coded and executed. The two techniques are:

- Code walkthrough: a review process wherein both the model design and the codes are presented to external parties. This process allows researchers to review their work and detect possible errors.
- Debugging: a process that search for abnormalities and solve errors. To debug we introduce into the model tests codes that would reveal any existing logical and programming errors.

4.4.2 Model validation

We acknowledge that it is difficult to validate our model against real-world data owing to the fact that our model is (i) qualitatively oriented, as it concentrates on the logical foundation of the interactions and mechanisms of agents, (ii) anachronistic, as the simulated world is built using data from many sources, not all of which are chronologically consistent, and (iii) theoretical, as the model, while constructed with Soc Trang Province in mind, does not reproduce the province in high resolution. There is no doubt that the model would not perform well with traditional statistical methods.

However, considering the purposes and the nature of our model, we argue that its validity should not be disregarded. As the model only aims to qualify the outcomes of interest, not to quantify or forecast, its statistical conclusion validity should take second place to logical validity. Therefore, we validate our model by (i) conceptually evaluating the structure of the submodels, and (ii) testing their behaviours using both uncertainty and sensitivity analyses.

Our submodels are conceptually justified as they are designed using secondary data obtained from the literature. Most assumptions are grounded in either data or established theories, and arbitrary assumptions are believed to be of minimal significance. Parameters are calibrated to at the very least achieve a resemblance to the real world.

4.4.3 Uncertainty analysis

Due to the presence of stochasticity in the model, the outputs of one simulation run have a certain degree of uncertainty built in. To account for this uncertainty, we follow convention and independently perform a number of replications for each scenario designed in Section 4.5. For each of the indicators, we compute their mean values and their confidence intervals at the 95% confidence level.

$$CI_{0.05} = \bar{X} \pm 1.96 \frac{s}{\sqrt{n}} \tag{4.18}$$

where $CI_{0.05}$ = 95% confidence interval
$\bar{X}$ = mean of indicator X
s = standard deviation of indicator X
n = number of replications

4.4.4 Sensitivity analysis

As our model is qualitative, we use the One-factor-at-a-time (OFAT) method to analyse the sensitivity of certain model parameters listed in Table 4.4. This method is chosen as it brings into light important aspects regarding qualitative the relationships between parameters and outputs (ten Broeke, van Voorn, & Ligtenberg, 2016). As a result, the parameters to be tested are selected for their relative importance to the model structure.

For each parameter, we run the model at its default and the extreme values of its admissible range for 10 replications. The rest of the parameters are set at their default values. The mean and the spread of the outputs will be considered.

4.5 Experiment design

We design two sets of scenarios to evaluate the impact of the rice-first agenda. The scenarios differ in policy setting and the presence of severe saltwater intrusion. The first set aims to study the rice-first agenda as a whole and consists of 4 scenarios (Table 4.2) The results from this set assess the impact of the rice-first agenda in the event of severe saltwater intrusion by comparing it with the hypothetical scenarios wherein no severe saltwater intrusion occurs.

	Without severe saltwater intrusion	With severe saltwater intrusion
With the rice-first agenda	S1	S2
Without the rice-first agenda	S3	S4

Table 4.2: Set 1 of scenarios

The second set of scenarios implements one measure in the rice-first agenda at a time at their default values, i.e. how they are currently set out in official documents, to compare and contrast their individual effect in the presence of severe saltwater intrusion. Afterwards, each measure is assessed at three different settings: “low”, “medium”, and “high” (Table 4.3).

	Land-use planning	Direct payment	Price support
	Minimum rice plan (%)	Payment amount (USD)	Profit margin (%)
Low	20	47 (default)	15
Medium	42 (default)	500	30 (default)
High	60	1,000	60

Table 4.3: Set 2 of scenarios

In scenarios with severe saltwater intrusion, the frequency and the magnitude of such events are the same and as described in Table 4.4. The indicators used to evaluate

Variable	Description	Default value	Range for OFAT
$\lambda_{s,r}$	Rate of saltwater intrusion from sea to river	0.45	0.1-1
$\lambda_{s,l}$	Rate of saltwater intrusion from sea to land	0.45	0.1-1
$\lambda_{r,l}$	Rate of saltwater intrusion from river to land	0.4	0.1-1
p	Likelihood of severe saltwater intrusion event	0.3	0.1-0.9
ν	Base magnitude of severe saltwater intrusion event	2	1-3
$p_{r,0}$	Price of rice at $t = 0$ (USD)	0.206	0.1-0.3
$p_{s,0}$	Price of shrimp at $t = 0$ (USD)	3.64	3-4
θ	Coefficient controlling for price variation caused by a change in supply	0.4	0.1-1
ω	Weight of the present information	0.2	0-1

Table 4.4: Model parameters used for sensitivity analysis

the impact of the measures of the rice-first agenda are given in Table 4.5. Each simulation run of each scenario lasts 50 iterations, which is the most common number of iterations used in ABMs that study land-use and land-cover change (Hailegiorgis et al., 2018). To ensure statistically useful output, all scenarios are replicated 100 times.

4.6 Summary

In light of climate change, the VMD is facing a dilemma. The traditional permanent double crop rice farming system has proved to be untenable when saltwater intrudes further and harder inland. The permanent double crop shrimp farming system—the popular alternative—is not environmental friendly and can add fuel to the fire. The alternating rice-shrimp farming system, the middle ground, is not preferred due to its economic and technical weaknesses in spite of its adaptive capability.

The existence of the rice-first agenda further complicates the situation. Prima facie, the rice-first agenda appears to be behind the times, promoting a livelihood that is no longer viable. However, there are good grounds for postulating that the abandonment of its measures might prompt a collective, unorganised switch to other livelihoods that may prove even more damaging in the long run. That few of the suppositions are evidence-

Outcome of interest	Indicator
Land use	Number of farmers practicing each farming system
Livelihood performance	Profit rate of each farming system (USD per capita)
Crop supply	Total yield produced (tonne)
Salinity distirbution	Number of plots in each salinity classification

Table 4.5: Indicators used to assess the rice-first agenda

based makes it more difficult for policymakers and the people of the VMD to find the right course of action.

Adding to the uncertainty is the fact that the economic system in the VMD is too complex for traditional policy assessment methods. Livelihood choices of farmers in the region depend not only on the physical conditions of their environment, but also on the choices of other farmers. The physical conditions of the environment depend not only on exogenous climate variables, but also in the livelihood choices of farmers. It is not easy to analyse these interlocking feedback loops with methodologies designed for more linear interactions.

ABM seems intuitively suited to study these complex interactions. Therefore, we have proposed an ABM that aims to qualitatively estimate the impact of the rice-first agenda on the environment, the economic interest of farmers in the region, as well as on food security. This model is made up of 3 submodels that integrate the environmental system with two levels of the human system: the social level in the form of an economy which includes the market as well as the government and their interventions, and the individual level in the form of an innate decision-making mechanism. The detail of the model is laid out following the ODD protocol, and the model is applied to the Soc Trang Province. The results obtained from the model is presented and discussed in the next chapter.

Chapter 5

Results and Discussion

5.1 Introduction

Our ABM was initialised as described in Section 4.3.5 with data gathered from the literature (Table A.1). The simulation environment was hosted on NetLogo version 6.2 on the macOS operating system. A total of 1300 simulation runs were performed, not including those performed for the sensitivity analysis. This chapter presents and discusses the results as well as the limitations of the model and recommendations for further study.

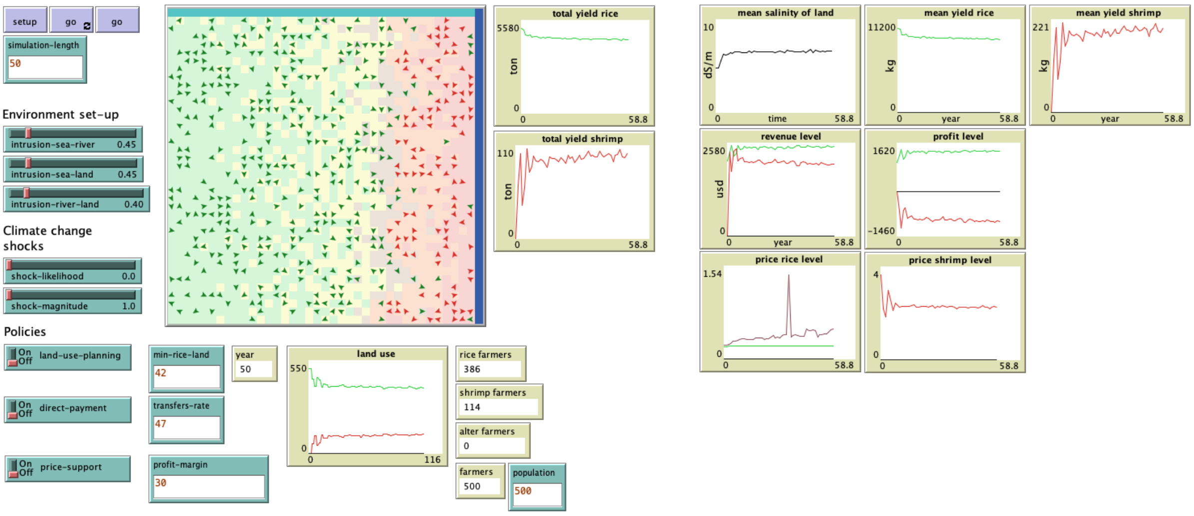
5.2 A note on model validity

As discussed in Section 4.3.1.2 and 4.4.2, the model is expected to produce two key observed patterns: farmers in the saline areas switching en masses to shrimp farming and farmers switching temporarily to the alternating farming system. Both these patterns have been observed. Figure 5.1 shows a graphical output demonstrating the first pattern. The second pattern can be gleaned from the frequent fluctuation of the number of farm agents practicing the alternating rice-shrimp farming system in Figure 5.3.

5.3 Simulation results: the impact of a policy regime switch

The first set of scenarios aim to answer the question: what would happen if the VMD abandoned completely the rice-first agenda. We consider both the cases where there is no severe saltwater intrusion and the scenarios where there is severe saltwater intrusion. The means and the confidence intervals are presented graphically below, and when the values of the time series exceed the selected scale, rescaled graphs can be found in Appendix C.

In terms of the environmental impact of the rice-first agenda, Figure 5.2 shows that



simulation-length 50
intrusion-sea-river 0.45
intrusion-sea-land 0.45
intrusion-river-land 0.40
shock-likelihood 0.0
shock-magnitude 1.0
On Off land-use-planning
On Off direct-payment
On Off price-support
min-rice-land 42
transfers-rate 47
profit-margin 30
year 50
rice farmers 386
shrimp farmers 114
alter farmers 0
farmers 500
population 500

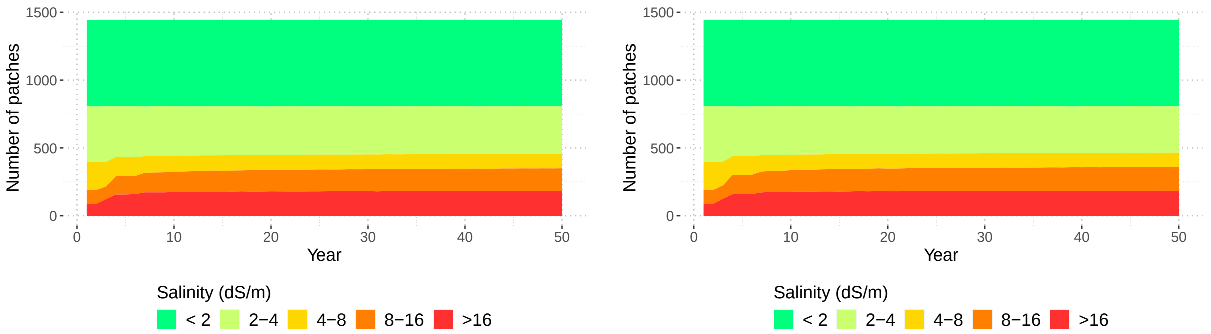
Figure 5.1: Netlogo GUI showing a land-use pattern equivalent to one documented in Liu et al., 2020

the presence of the rice-first measures makes no discernible difference in both types of scenarios. When there is no severe saltwater intrusion, the sizes of the areas with medium, high, and very high salinity are always small and only increase by a fraction throughout the simulation. The size of the area with no salinity remains the same.

When there is severe saltwater intrusion, the areas with no and low salinity predictably contract by more than half, and the area with high salinity expands correspondingly. In the scenario with the rice-first agenda, the expansion happens a little more gradually, judging from the slightly flatter slopes, and the area with low salinity, which is still suitable for rice farming, is marginally larger than in the scenario without the rice-first agenda. The areas with medium and very high salinity do not change much in size are virtually the same in both types of scenarios.

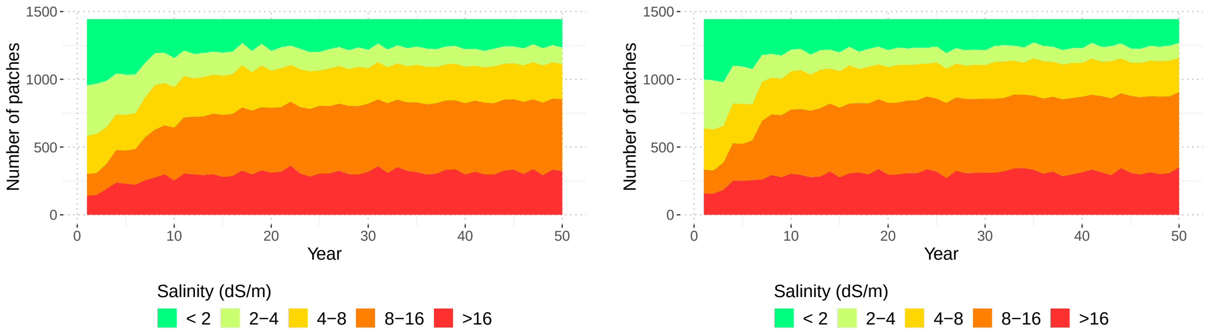
Keeping in mind that even with severe saltwater intrusion, the saltwater typically is flushed away within the year both in practice and in the simulations, the resulting expansion of saline areas in the scenarios where there is severe saltwater intrusion can be attributed to an expansion in shrimp farms, as recorded in Figure 5.3. It is here that we can observe an impact of the rice-first agenda: in scenarios where the rice-first measures are enforced, there are farm agents who choose the alternating rice-shrimp farming system, as opposed to none in scenarios where the rice-first measure are not enforced. In the scenarios with severe saltwater intrusion, the rice-first agenda also manages to keep more farm agents in rice farming. Consequentially, in the scenario with severe saltwater intrusion and without the rice-first agenda, there are more farm agents who choose the permanent shrimp farming system than in any other scenarios.

This translates into differences in total crop yields between scenarios. In all scenarios, the total yield of rice decreases at first as the farm agents adapt to the normal saltwater intrusion before reaching stability (Figure 5.4). The difference lies in the magnitude as well as the duration of the decrease. In scenarios where there is severe saltwater intrusion, the total yield of rice decreases almost in half and only reaches stability in year



(a) With the rice-first agenda and with no severe saltwater intrusion

(b) Without the rice-first agenda and with no severe saltwater intrusion



(c) With the rice-first agenda and with severe saltwater intrusion

(d) Without the rice-first agenda and with severe saltwater intrusion

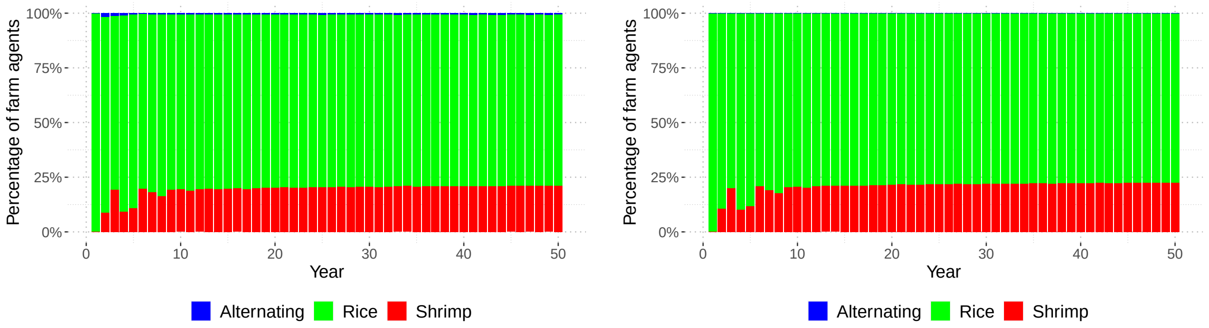
Figure 5.2: Salinity distribution in the region under different scenarios

20. In comparison, in scenarios where there is no severe saltwater intrusion, the total yield of rice decreases only marginally and reaches stability in less than 10 years.

Once again in scenarios where there is no severe saltwater intrusion, the rice-first agenda has virtually no impact. In scenarios where there is severe saltwater intrusion, the rice-first agenda neither prevents nor slows down the yield decline, but it does manage to cushion the decline to a small extent. Without the rice-first agenda, the total rice yield would decline slightly more.

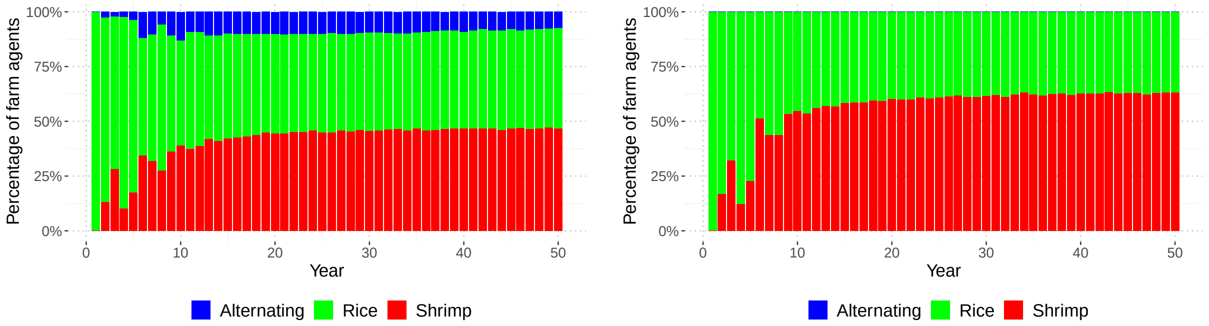
We observe similar patterns with the total yield of shrimp (Figure 5.5). In all scenarios, the total yield of shrimp increases sharply at first as farm agents in saline areas switch to shrimp farming, then adjusts as some farm agents switch back and forth, and finally stabilises. Unlike in the case of rice yield, the adjustment periods are roughly similar in all scenarios. As we have come to expect, the evolutions of the total yield of shrimp are almost identical in the two scenarios with no severe saltwater intrusion, further confirming that the rice-first agenda does not have an impact in this hypothetical case.

In scenarios with severe saltwater intrusion, the rice-first agenda surprisingly enables the total yield of shrimp to reach a slightly higher stability level despite having fewer shrimp farm agents. A switch away from the rice-first agenda would increase the number of shrimp farm agents but decrease the total yield of shrimp produced in the region. This asymmetry in the number of farmers and the total yield cannot be attributed to the



(a) With the rice-first agenda and with no severe saltwater intrusion

(b) Without the rice-first agenda and with no severe saltwater intrusion



(c) With the rice-first agenda and with severe saltwater intrusion

(d) Without the rice-first agenda and with severe saltwater intrusion

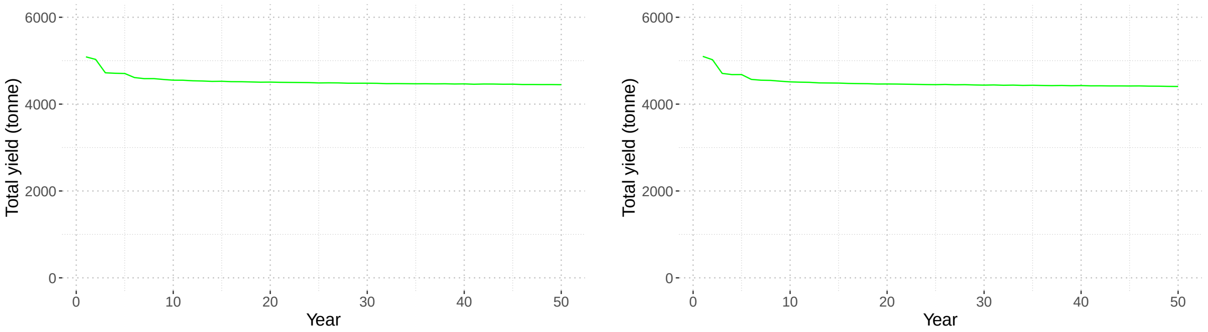
Figure 5.3: Livelihood choices in the region under different scenarios

additional number of farm agents practicing the alternating rice-shrimp farming system that the rice-first agenda generates, since technically they are only able to produce half the amount of shrimp that an equal number of permanent shrimp farmers can produce. It is the result of the (simulated) fact that the more shrimp farms there are in an area, the higher the disease risk becomes, and the lower the expected yield is.

As for crop prices (Figure 5.6), in the scenarios without severe saltwater intrusion, the price floor of rice set by the rice-first agenda is slightly higher than the market price. The market prices of shrimp in both scenario are predictably the same.

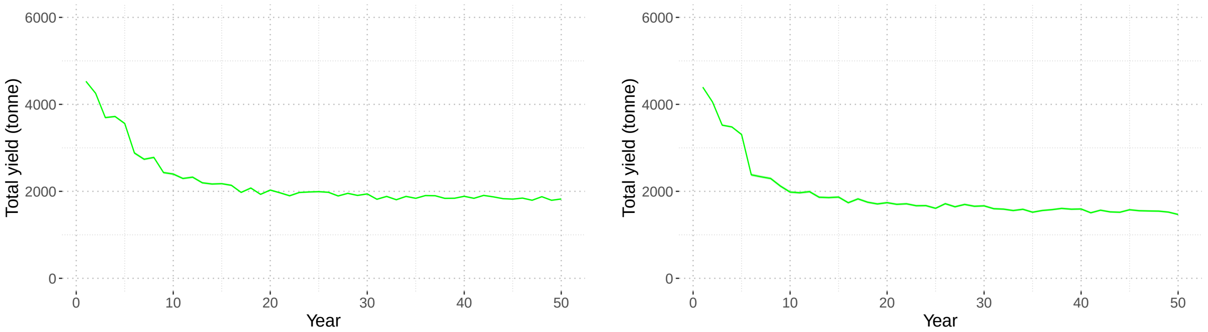
There is a marked difference between the scenario where there is both the rice-first agenda as well as severe saltwater intrusion and the scenario where there is severe saltwater intrusion but no rice-first measures implemented. In both scenarios, prices become more uncertain in comparison to the case where there is no severe saltwater intrusion, as evidenced by the visible confidence intervals. However, in the scenario where the rice-first measures are enforced, the price of shrimp is higher than the price of rice, and both prices trend upwards gradually throughout the simulation. By contrast, in the scenario where the rice-first measures are not enforced, the price of rice shoots up significantly. Given that the difference between the total rice yields of these scenarios is minimal, this result appears rather curious.

To explain this, we exploit one of the advantages that ABM offers: the ability



(a) With the rice-first agenda and with no severe saltwater intrusion

(b) Without the rice-first agenda and with no severe saltwater intrusion



(c) With the rice-first agenda and with severe saltwater intrusion

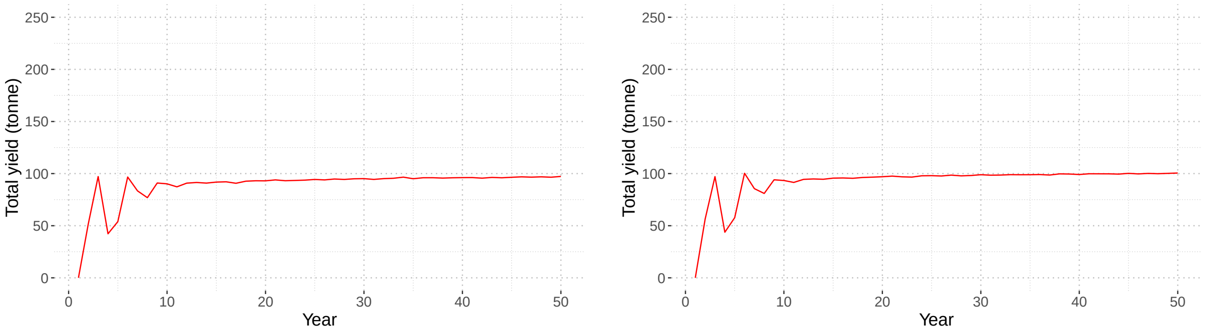
(d) Without the rice-first agenda and with severe saltwater intrusion

Figure 5.4: Total yield of rice in the region under different scenarios

to “inspect under the hood” and investigate the micro dynamics that give rise to these aggregate, macro results. Consider the case where there is severe saltwater intrusion. In the scenario where the rice-first measures are implemented, there is only 1 land-use pattern observed at different degrees: rice farm agents gradually switch to shrimp farming, with a small degree of back-and-forth switching between three farming systems, no doubt in areas with medium and high salinity where it is still possible to cultivate rice along with shrimp (Figure:5.7).

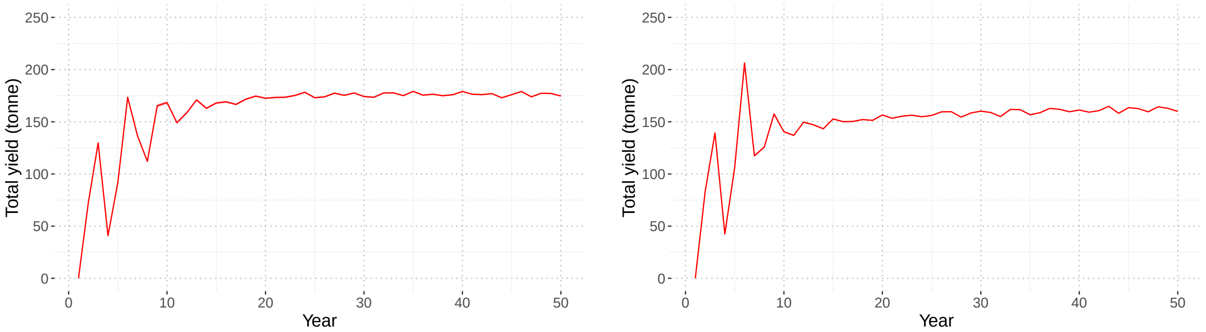
In the scenario where the rice-first measures are not implemented, there are 3 different land-use patterns observed. In the first pattern (Figure 5.8a), farm agents adapt to the normal saltwater intrusion then settle down until a severe saltwater intrusion event prompts them to revise their livelihood options.

In the second pattern (Figure 5.8b), a severe saltwater intrusion event happens early in the simulation, which makes a sizeable number of farm agents switch to shrimp farming, depressing the price of shrimp significantly. This leads many new shrimp farm agents to switch back to rice in the next period, causing a decline in the total shrimp yield and an increase in the price of shrimp, which incentivises many farm agents to once again switch back to shrimp farming. Unlike in the scenario where the rice-first agenda is in place, this cycle only happens a few times before each farming system reaches its stable level and oscillates there.



(a) With the rice-first agenda and with no severe saltwater intrusion

(b) Without the rice-first agenda and with no severe saltwater intrusion



(c) With the rice-first agenda and with severe saltwater intrusion

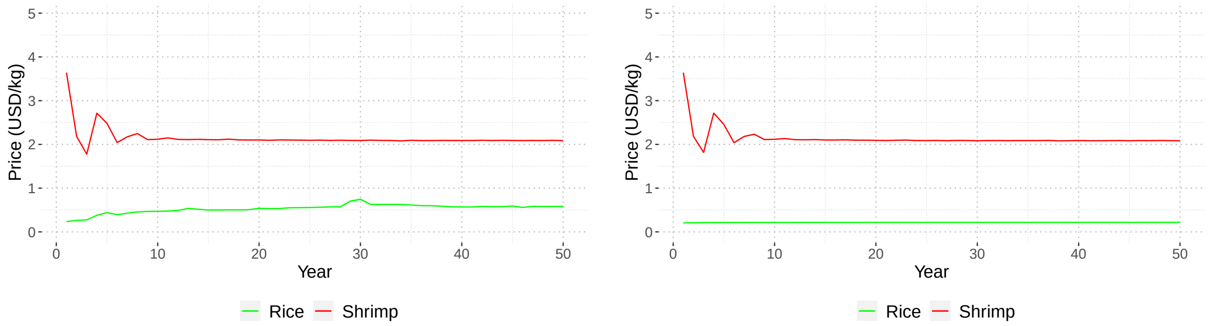
(d) Without the rice-first agenda and with severe saltwater intrusion

Figure 5.5: Total yield shrimp in the region under different scenarios

In the third pattern (Figure 5.8c), which is the extreme version of the second one, farm agents collectively switch back and forth between rice farming and shrimp farming. It is this collective movement that must have propelled the market price of rice skywards as observed in Figure 5.6d. It must have also affected the overall salinity distribution of the region and render the entire region hostile to rice. As a result, most if not all farm agents switch to shrimp farming. This pattern occurs 28 times out of the 100 simulations.

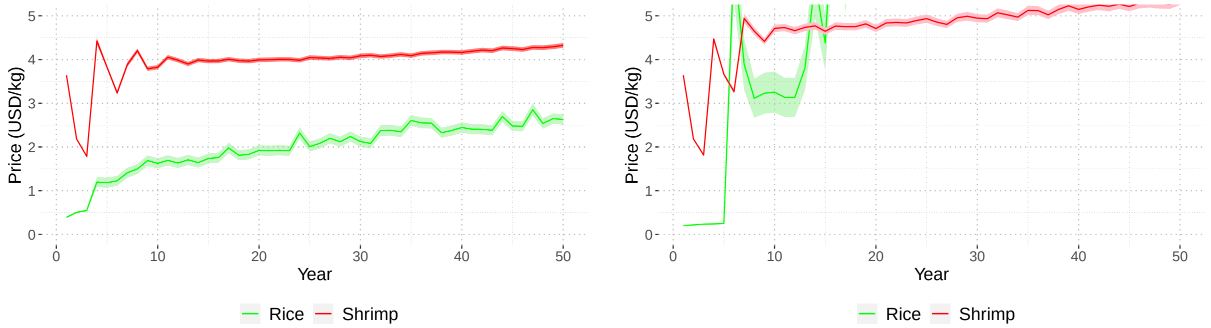
That a large part of the region is unsuitable for rice farming appears to be the only rational explanation for the profit gap between the permanent rice farming system and the other two (Figure 5.9). In all but one scenarios, farm agents practicing the permanent shrimp farming system earn a negative profit on average. This result is economically untenable and only makes behavioural sense if we argue that many farm agents choose to suffer such losses because they have no other choices: their land is so saline that any options other than permanent shrimp farming will lead to even greater losses.

Figure 5.9 also implies that without the rice-first agenda, income inequality would be more significant, as the few rice farm agents living in areas with no or low salinity would earn a huge profit, while the shrimp farming majority would struggle to break even.



(a) With the rice-first agenda and with no severe saltwater intrusion

(b) Without the rice-first agenda and with no severe saltwater intrusion



(c) With the rice-first agenda and with severe saltwater intrusion

(d) Without the rice-first agenda and with severe saltwater intrusion

Figure 5.6: Crop prices in the region under different scenarios

5.4 Simulation results: the efficacy of the rice-first measures

The second set of scenarios aims to ascertain the effectiveness of individual measures. By effectiveness we mean whether or not the measures have an impact that can be considered in line with the government's desired results. We consider the case where there is severe saltwater intrusion and implement each measure separately. We also experiment with different measure settings to gauge the relative effects of the measures.

Figure 5.10 shows that the only effective measures are land-use planning and direct payment. It is clear that land-use planning is the main measure behind the impact of the rice-first agenda set, as the results obtained from simulations which implement only the land-use planning are almost the same as the ones obtained from simulations which implement all three measures. The effects of the direct payment measure are much more subtle but also heading in the same direction.

Figure 5.10i shows that in the scenario where only the price support measure is implemented, the price of rice increases sharply throughout the simulation, not unlike the scenario where no rice-first measures are put in place (Figure 5.6d). This certainly emphasises the distorting effect that a price floor—one that is strictly adhered to as in our simulations—has on the market.

Unsurprisingly, the land-use planning measure at the low setting has minimal impact in terms of livelihood choices and does let the price of rice increase considerably (Figure 5.11). However, the additional effect that the high setting brings about is small. Moreover, at the high setting, the land-use planning measure leads to a decrease in the total yield of shrimp but no compensatory increase in the total yield of rice.

At higher settings, the direct payment measure increases the number of farmers who practicing the alternating rice-shrimp farming system considerably (Figure 5.12). This implies that the amount of direct payment as currently set by the government is too small to have an impact. At the highest setting, the direct measure has more success in preventing the salinitisation of the region as well as ensuring high profit for farm agents. But the tradeoff lies in the high inflation that the direct measure at higher settings can set off.

The different settings of the price support measure make almost no difference in impact on all of our indicators (Figure 5.13). The only difference is the duration of rice price stability: price floors set at a higher profit margin stabilise the price of rice at the beginning of the simulation for much longer.

5.5 Sensitivity analysis

Sensitivity tests for selected parameters were carried out as discussed in Section 4.4.4. The results are reported in Appendix B. These tests indicate that the model has a low sensitivity to the majority of the selected parameters. Most notably, the model is moderately sensitive to low levels of rice price B.6 and high levels of shrimp price B.7. The model is also more sensitive to the middle of the admissible range for p, the likelihood of a severe saltwater intrusion event. On the other hand, the model is highly sensitive to changes in θ, the coefficient controlling for price variation caused by a change in supply.

Overall, the model appears to be robust to parameter changes. However, it should be noted that (i) not all parameters are tested, (ii) the number of runs and the tested ranges for each parameter are limited, and (iii) the OFAT method only indicates robustness to individual parameters and does not consider interaction effects (ten Broeke et al., 2016).

5.6 Discussion of results

On the whole, the results from our model suggest that a policy regime switch away from the rice-first agenda might spell trouble for the environment and the food security of the region. What the rice-first measures are able to do is to regulate the adaptation activities of the farmers, making sure that any livelihood and land-use changes happen gradually. This keeps the markets stable and prevents crises in which a shortage in supply causes prices to skyrocket. Without the rice-first measures, uncertainty increases, and there is a significant chance that a severe natural disaster would trigger maladaptation on a large scale, which would alter the environment for the worse, upset the markets, and precipitate high inflation.

Within the rice-first agenda, there is a stark difference between the efficacy of different measures. The land-use planning measure appears to already be formulated well, with changes in the setting bringing only a small amount of additional benefit that would not offset the increasing cost of enforcement. The direct payment measure, on the other hand, is set too low to have an effect. Increasing the amount of subsidy to rice production would incentivise farmers to choose either the permanent rice or the alternating rice-shrimp farming system, which does indeed help limit the salinitisation of the region. The price support measure brings no benefit. More detrimentally, it can distort the market to the point that a severe shock to crop production can trigger rapid and excessive inflation.

The ultimate goal of policy interventions is to generate the most benefit at the lowest cost in the long run. Additional benefit achieved from stricter land-use planning or higher subsidy has its pecuniary, economic, social, and political cost. In addition, our model also assumes perfect compliance on the part of farm agents. This is not the case in practice, as shown in Section 2.4.1. Regarding land-use planning, the cost of enforcement and the risk of social discontent need to be taken into account. Regarding subsidy, especially increases in subsidy, the long-run economic cost might outweigh any potential benefit. Results from models such as ours should only serve as guidelines rather than prescriptions.

5.7 Limitations of the model

This model has two types of limitations: the first type concerns the conceptualisation and the design of the model, and the second type pertains to its implementation as well as its application.

With regard to model conceptualisation and design, the main limitation of this model is its oversimplification of key mechanisms, namely the saltwater intrusion process, the market mechanism, and the decision-making mechanism. One of the great challenges of ABM is to find the middle ground between realism and tractability. The more realistic a model aspires to be, the more complex it becomes. The more complex a model is, the easier it is for researchers to lose their way in all the details, and the less user-friendly and, in worst-case scenarios, less usable it becomes as discussed in Section 3.5. In an effort to reach our main goal, which is to complete a workable model from scratch, in the time allotted, we have erred on the side of simplicity and opted for the most straightforward representations of these highly complex mechanisms.

Specifically, we have reduced saltwater diffusion—an intricate natural process that depends on numerous factors—to simplistic equations based solely on observed outcomes. While their product does resemble the current actual situation on a surface level, our equations, and by extension our end results, are static and cannot account for variations or future evolution. We recognise that this strictly restricts the generality and the forecasting capability of the model, preventing it from fully taking advantage of ABM's power to handle unexpected consequences.

Similarly, we have made strong assumptions regards the input and output markets. By maintaining a constant cost structure, we have eliminated the possibility of any development in the input markets. By assuming that the output markets always clear, neglecting the demand side, and imposing a simple adaptive price updating mechanism in its place, we have cut off our modelled producers from the outside world. While this is not too fundamental a flaw, the crudeness and the innate asymmetry in the price revision process have produced several curiosities in the long term during our trial runs of the model, wherein prices trend upwards as the quantity of supply falls. The bare-bones foundation of our economic submodel means that the results are pulled inordinately by the saltwater intrusion and the behavioural submodels, and our model has not been able to reach a more economically interesting place.

Our reactive decision-making mechanism also pales in comparison to the complexity of proactive farmers in practice. We have not considered many substantial direct interactions among farm agents, many of which have been well documented such as knowledge transfer and imitation (see for instance Baum, 2018; Montes de Oca Munguia, Pannell, and Llewellyn, 2021; Quy-Hanh and Hans-Dieter, 2011; Schmit and Rounsevell, 2006; H. T. M. Vo, Van Halsema, Hellegers, Wyatt, and Nguyen, 2021). For a region with an entrenched history of collective agricultural production, a strong communal spirit, and a heavy emphasis on trust, this omission is egregious. The lack of learning as well as the assumption of perfect sensing are also unrealistic, chosen for their convenience and nothing more. The effect that these assumptions have on our models is neither qualified nor quantified, and would demand greater attention when the model is developed further.

On a minor note, we have put aside many other aspects of an agricultural economy such as the land market, the financial market, other adaptation options, and farmer networks. While this is a deliberate choice as these aspects lie beyond our immediate interest, it does place a limit on what observations we can gather from the model, and how close the model gets to the real economy.

With regard to model implementation and application, there are four key limitations. First, data availability, or the lack thereof, has been a significant issue. This is partly an expected challenge of ABM, and partly the result of our decision to use secondary data. While we have tried our utmost to search for the required data, the insufficient statistical infrastructure in the VMD means that not all of our parameters are available. In such cases, educated and justifiable guesses have been made to the best of our ability.

Second, how we initialise the model presents several shortcomings. We have chosen to keep the initial agent population homogenous, disregarding ABM's key advantage of being able to handle a high degree of heterogeneity. Although there is a record of a fairly homogenous population in the VMD in the early 2000s, we have combined it with the 2012 cost structure due to the aforementioned lack of data. While we stand by our opinion that a homogenous population can and does provide insightful information regarding the simulated system, this mismatch makes our model atemporal and almost impossible to validate against real-world data.

The cost structure and the calibration of the price updating mechanism also produce abnormalities. For instance, according to our model, with the current set of prices and costs, farm agents choose to switch from cultivating rice to cultivating shrimp permanently because they have no other choices and not because shrimp farming is a more economically attractive option. Farm agents located in areas suitable for rice farming have no incentive to switch to shrimp farming; farm agents located in areas hostile to rice have to switch even if shrimp farming has a negative profit rate on average. The profit gap between rice farming and shrimp farming is not recorded in the literature and goes against case studies as well as anecdotal evidence. Additionally, farm agents located in areas so saline that even shrimp farming is unprofitable switch back to rice because it generates the least lost. This behaviour does not correspond to any observed land-use patterns and needs to be addressed.

Third, although a quantitative analysis is not our goal, the lack of statistical testing as well as the fact that the majority of our results are derived from interpretations of graphical outputs does diminish the credence of our research. As it stands, our model only qualifies as a qualitative emulation of macro features at best and as a caricature of the real world at worst.

Finally, contrary to our focus on micro interactions in earlier chapters, we have spent more time with the macro results than with the micro dynamics that give rise to them. Since we have also conducted a limited number of runs, this lack of attention means that we might have failed to obtain crucial data, such as additional land-use patterns for each scenario. Together with the narrow ranges of values used for the sensitivity analysis, this reflects our limited computational capability and lessens our contribution to answering the research question.

5.8 Recommendations for further study

In a sense, the limitations of the model present opportunities for further study. To continue working with the model, the first course of action would be to address its conceptualisation and design weaknesses. By virtue of the modularity of ABM, each of the submodels can be refined separately then rejoined later. The saltwater intrusion submodel can be opened up to include significant exogenous variables that would offer a simulation closer to reality and improve our understanding of the co-evolution of the human and environmental systems. Advancements in hydrology would certainly aid this effort, and collaboration with other fields is much encouraged to ensure verifiable results.

Regarding the economic submodel, it is essential that the nexus between yield, price, and profit is revised to produce results more in line with both theories and observations. The price mechanism in particular would require a fresh look, with the addition of either the demand side or external data sources. The cost structure, while sound in theory, would benefit from further calibration. Farm accounting can also be fleshed out to complete the financial profile of farm agents.

There are many ways to improve the behavioural submodel. The neoclassical assumption of profit maximisation can be relaxed to admit other decision theories such as the theory of planned behaviour and the emotion theory of decision making, as well as more sophisticated agent architectures like the Belief-Desire-Intention or the Soar architecture. It is recommended that direct interactions among farm agents be established to better emulate both the individual farmers and the farmer communities in the VMD.

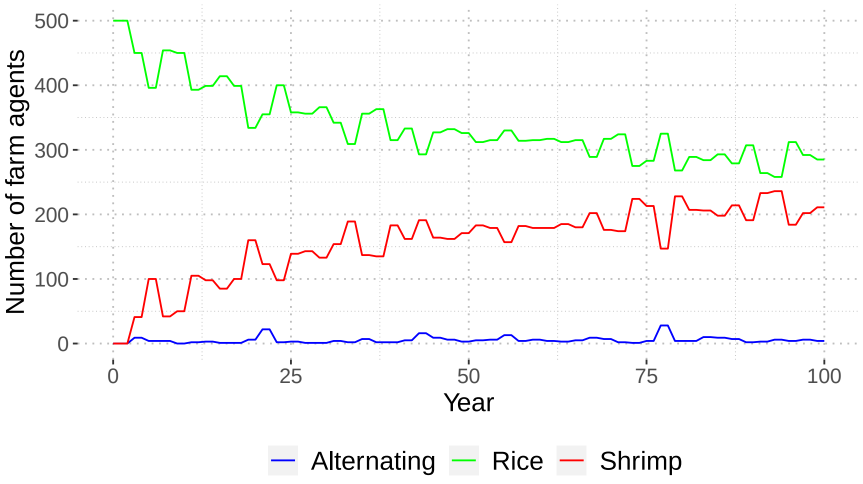
In terms of implementation and application, it is most advisable that primary data be collected via surveys to make sure that (i) the model has a consistent initial stage, and (ii) the results can be validated against real-world data, especially when the model moves on to higher levels of validity. A complete set of survey data would also enable researchers to set up agent populations with various degrees of heterogeneity, allowing them to make full use of the potential of ABM. More comprehensive parameter sweeps and sensitivity analyses can be performed to explore the parameter space and examine the robustness of emergent attributes more thoroughly. More suitable verification and validation techniques should also be employed to increase confidence in the model.

Once the model achieves quantitative validity, researchers can strive to obtain quantitative results and test out the forecasting potential of ABM. For ABMs to compete with current state-of-the-art models in forecasting, much more work and input data would be required. But we believe that this is going to be a worthy endeavour, considering the many possible and beneficial applications such as stress-testing and policy impact prediction.

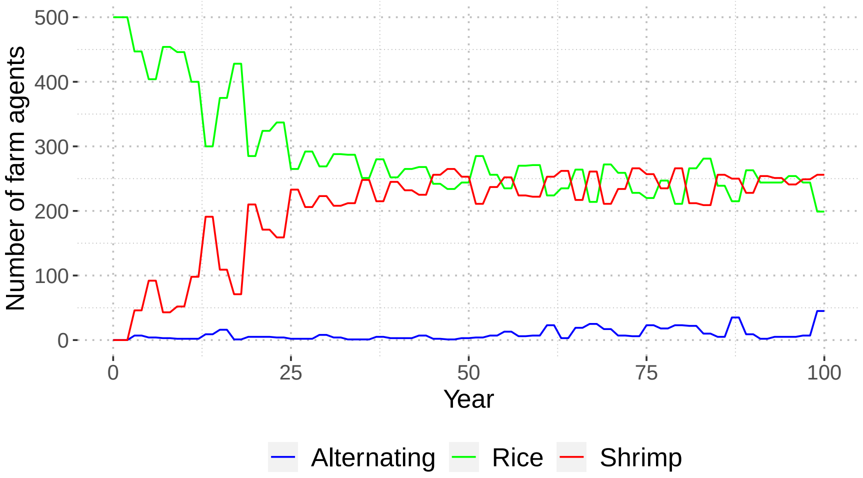
After addressing the limitations, researchers can extend the model by adding the land market and the financial market. A more complete set of adaptation options, which includes non-farm economic activities, quitting the agricultural sector, and out-migration, would be particularly interesting to investigate, despite its intensive data processing requirement imposed on not just the computer platform that hosts the model but also the agents themselves.

Regarding the research questions, while our results are qualitative and should be subject to ample scrutiny, they do offer many propositions that hitherto have not been considered. These can help guide the thinking process of researchers and form the basis for future research topics.

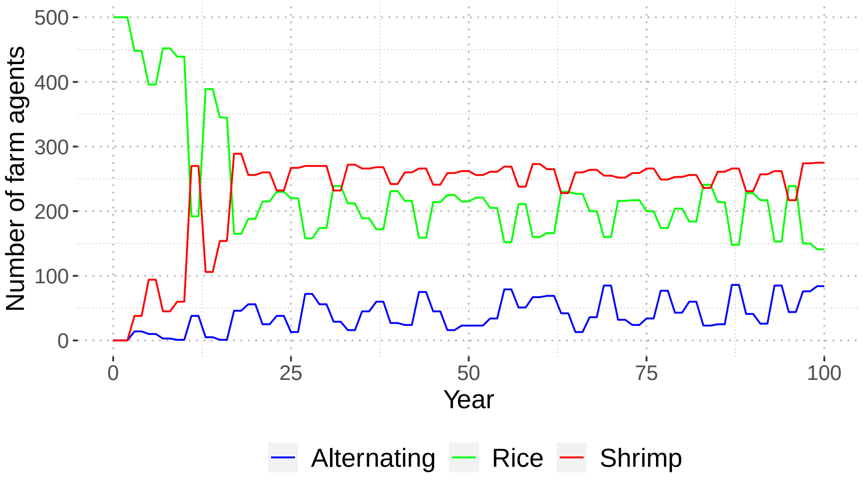
The flexibility of ABM means that there is unlimited potential for model extensions; the sky is truly the limit. However, interested researchers are advised to bear in mind that any future developments and extensions should be ultimately driven by well-formulated research questions. A sharp knife is as good as a blunt one when used to hammer a nail. A tool is only useful if it is used correctly.



(a) Land-use pattern 1

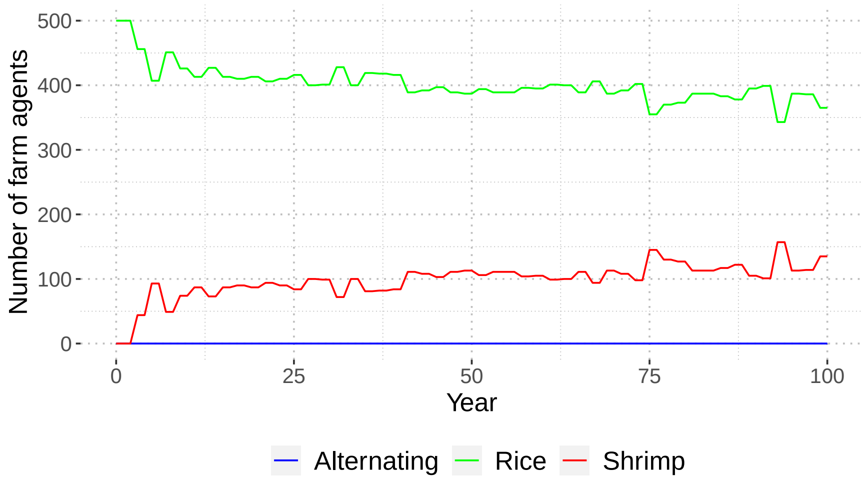


(b) Land-use pattern 2

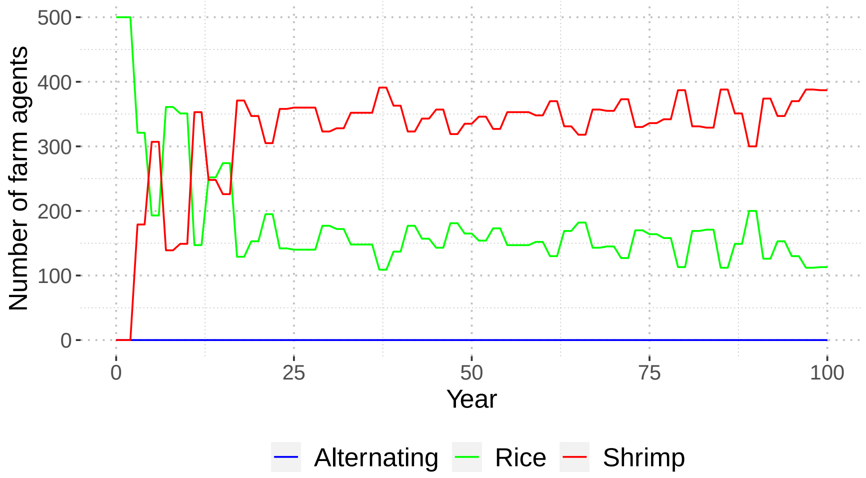


(c) Land-use pattern 3

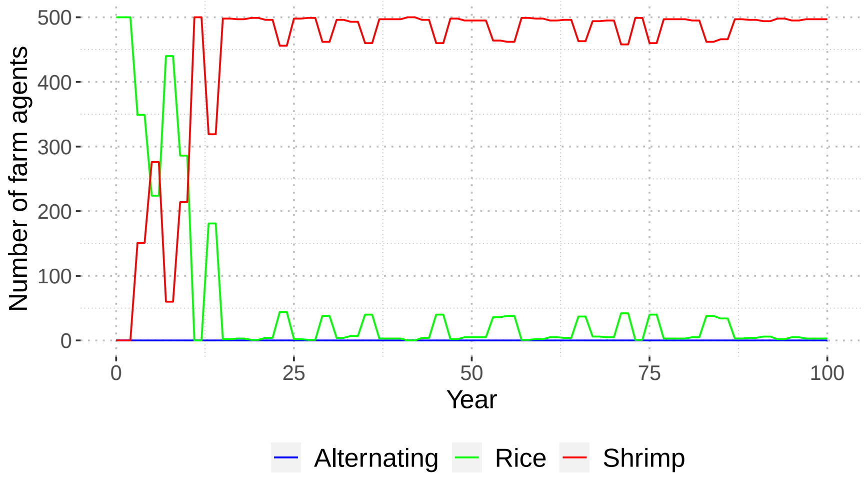
Figure 5.7: Land-use pattern in scenario with the rice-first agenda and with severe saltwater intrusion



(a) Land-use pattern 1

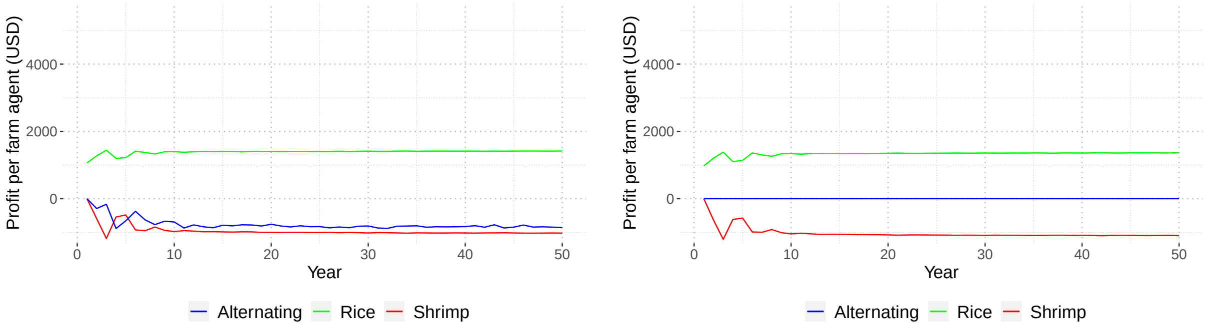


(b) Land-use pattern 2



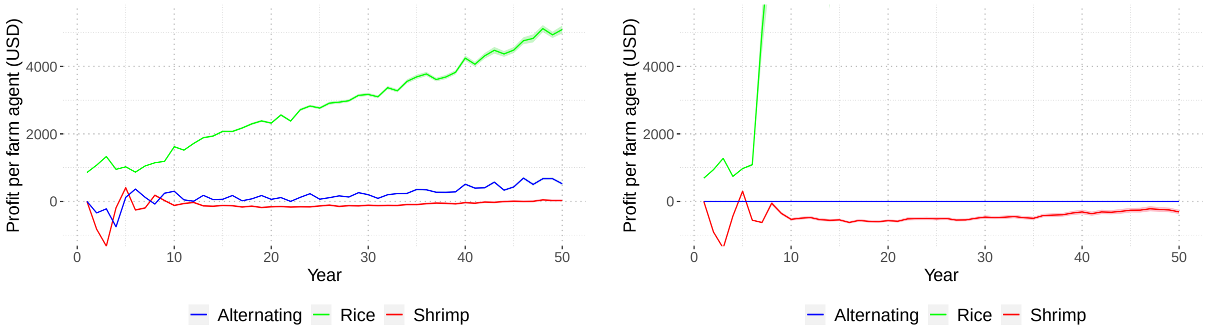
(c) Land-use pattern 3

Figure 5.8: Land-use pattern in scenario without the rice-first agenda and with severe saltwater intrusion



(a) With the rice-first agenda and with no severe saltwater intrusion

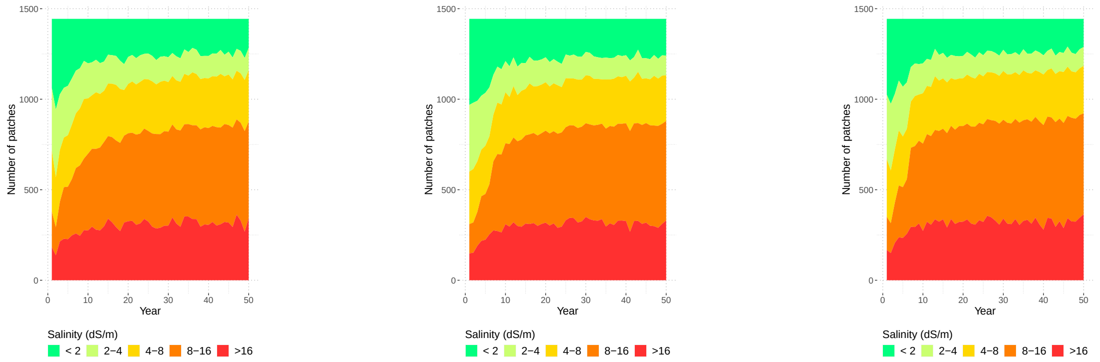
(b) Without the rice-first agenda and with no severe saltwater intrusion



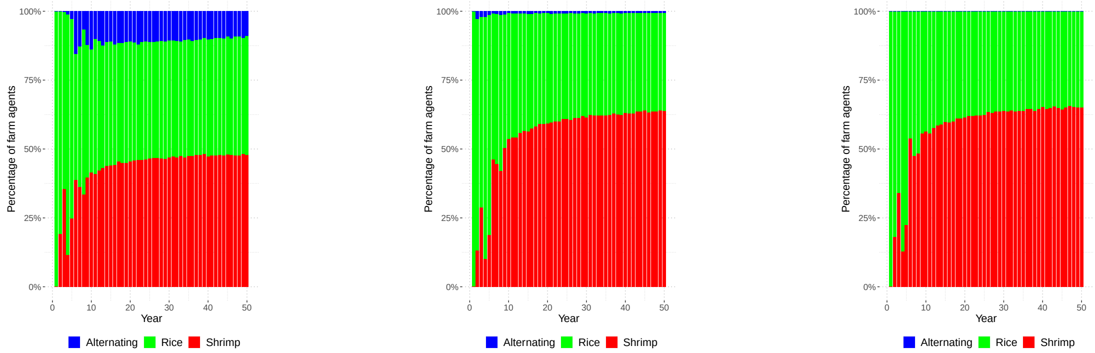
(c) With the rice-first agenda and with severe saltwater intrusion

(d) Without the rice-first agenda and with severe saltwater intrusion

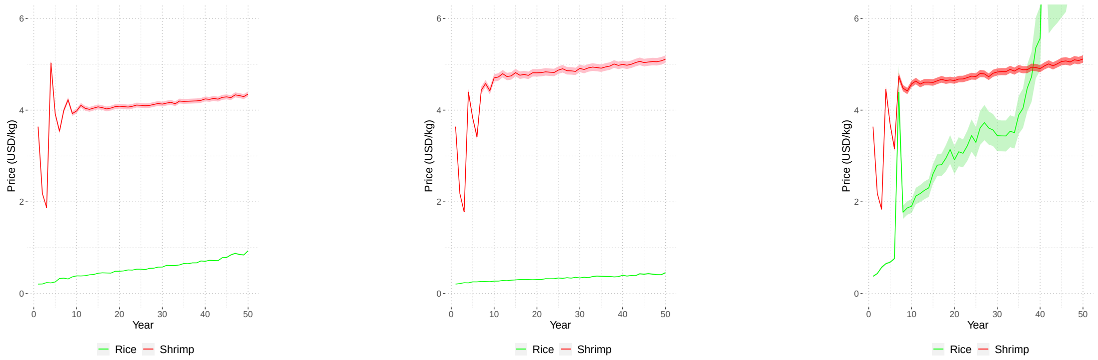
Figure 5.9: Profit rates in the region under different scenarios



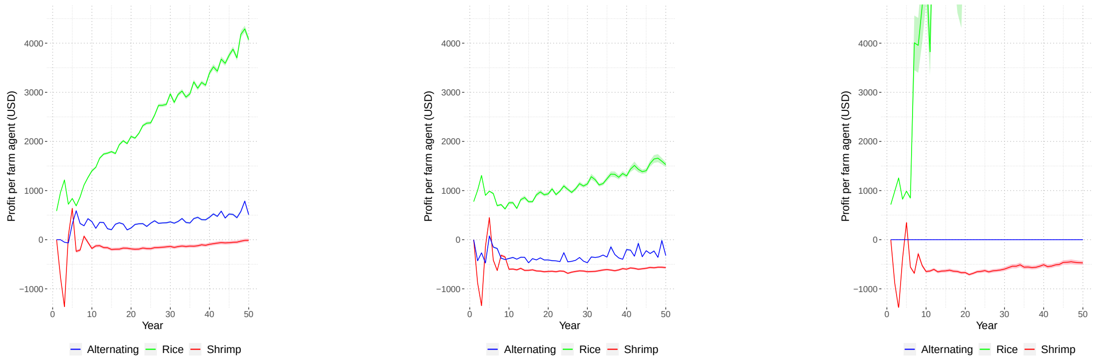
(a) Land-use planning (b) Direct payment (c) Price support



(d) Land-use planning (e) Direct payment (f) Price support

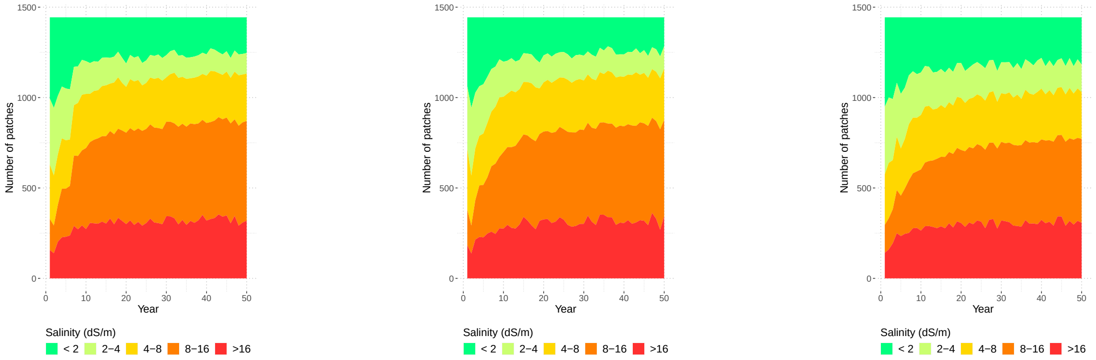


(g) Land-use planning (h) Direct payment (i) Price support

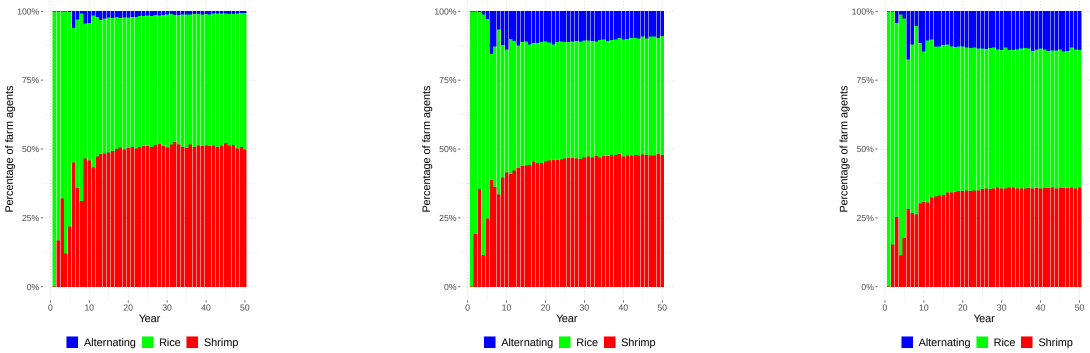


(j) Land-use planning (k) Direct payment (l) Price support

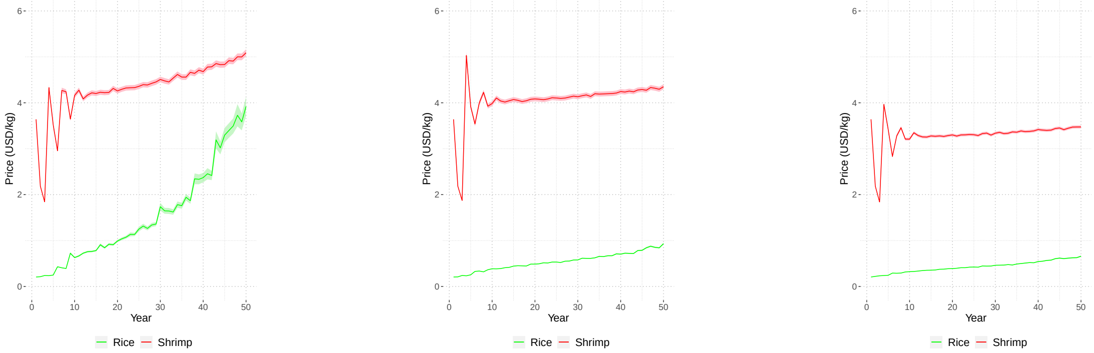
Figure 5.10: Impacts of different measures
on salinity distribution (a, b, c), livelihood choices (d, e, f), crop prices (g, h, i), and profit rates (j, j, l)



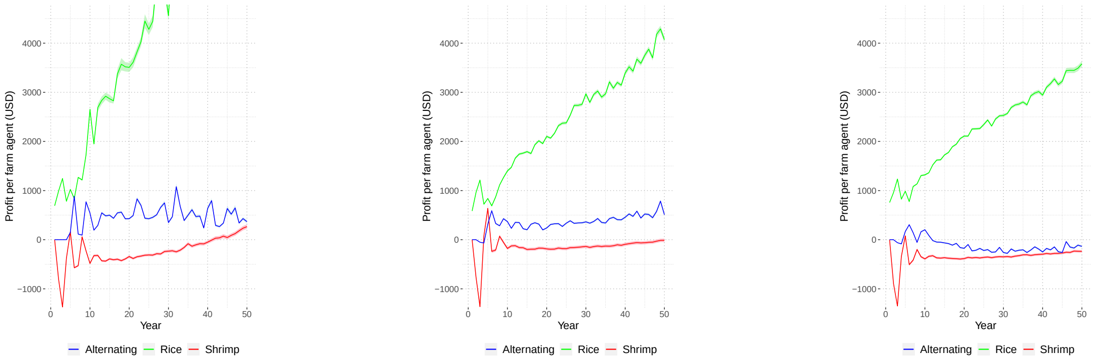
(a) 20% (b) 42% (c) 60%



(d) 20% (e) 42% (f) 60%

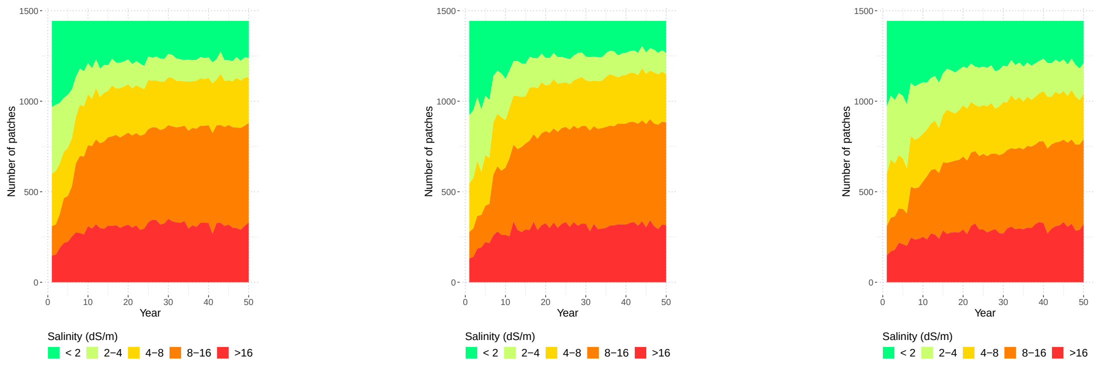


(g) 20% (h) 42% (i) 60%

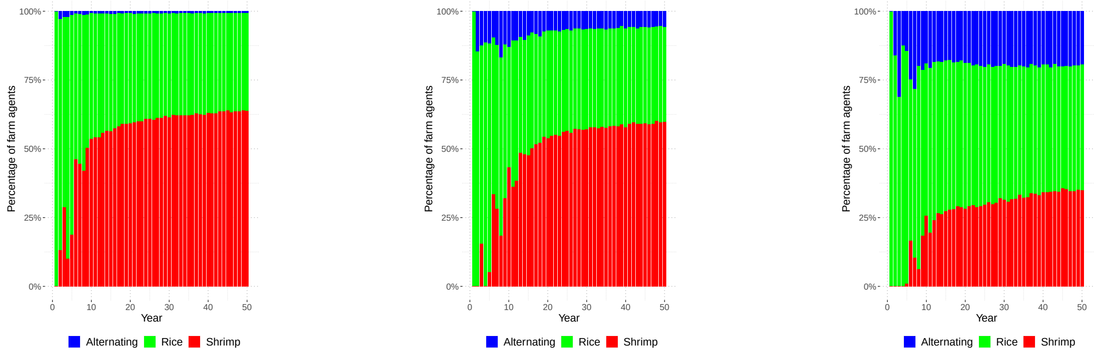


(j) 20% (k) 42% (l) 60%

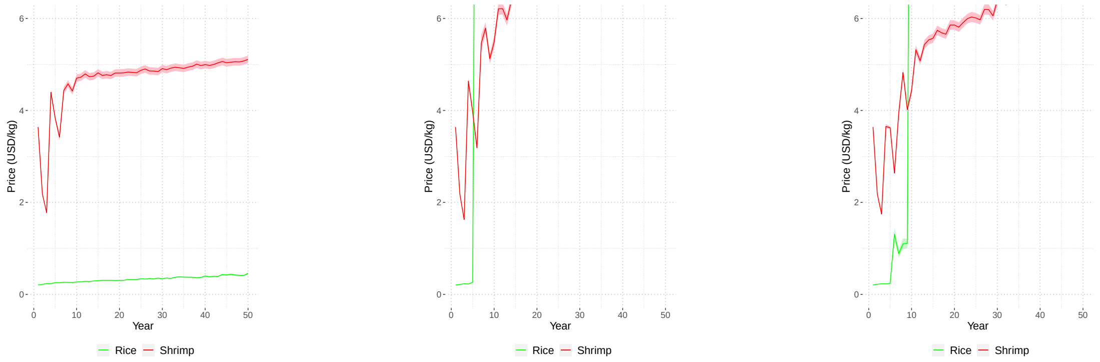
Figure 5.11: Impacts of different settings of the land-use planning measure on salinity distribution (a, b, c), livelihood choices (d, e, f), crop prices (g, h, i), and profit rates (j, j, l)



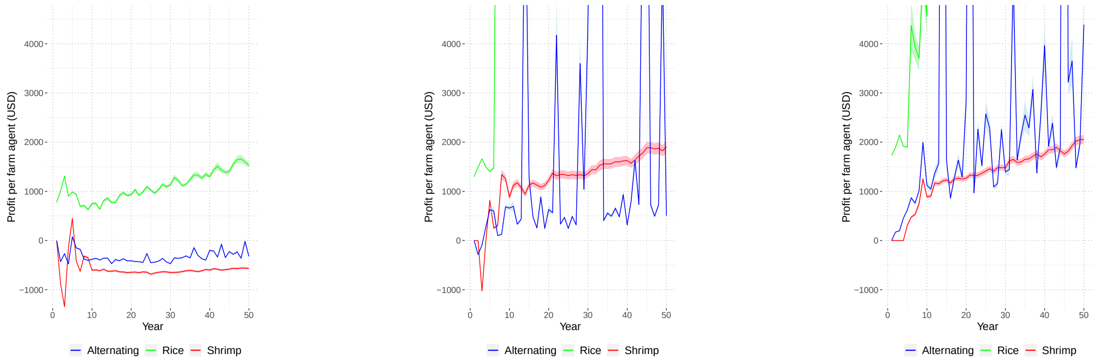
(a) 47 USD (b) 500 USD (c) 1,000 USD



(d) 47 USD (e) 500 USD (f) 1,000 USD

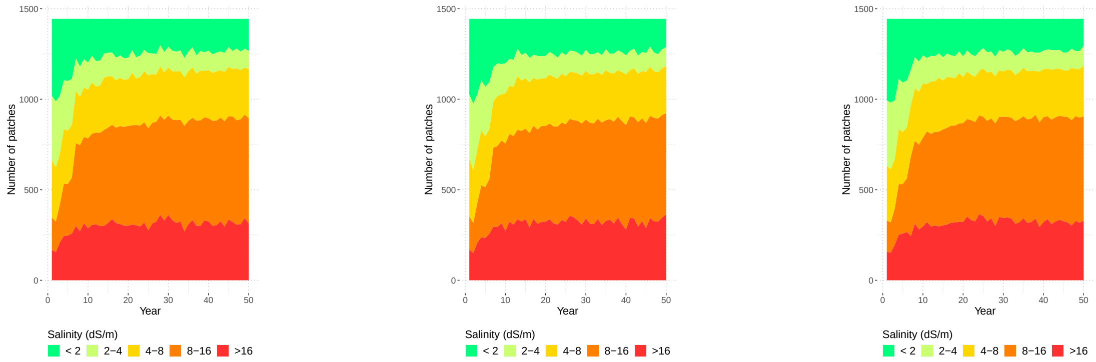


(g) 47 USD (h) 500 USD (i) 1,000 USD

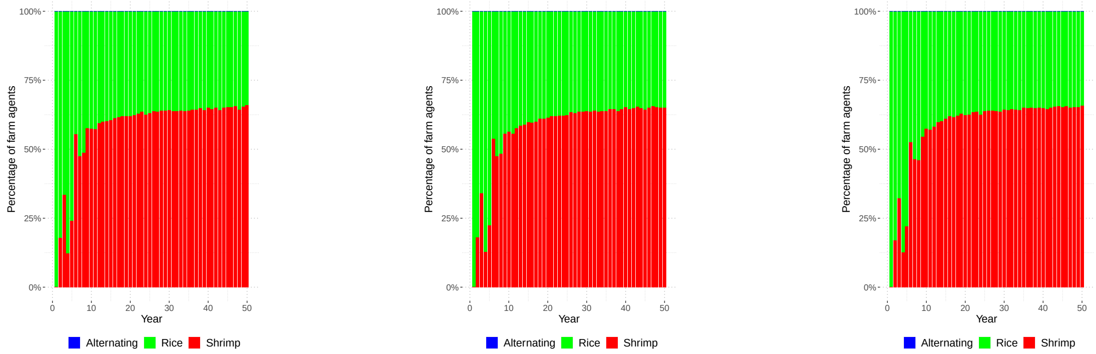


(j) 47 USD (k) 500 USD (l) 1,000 USD

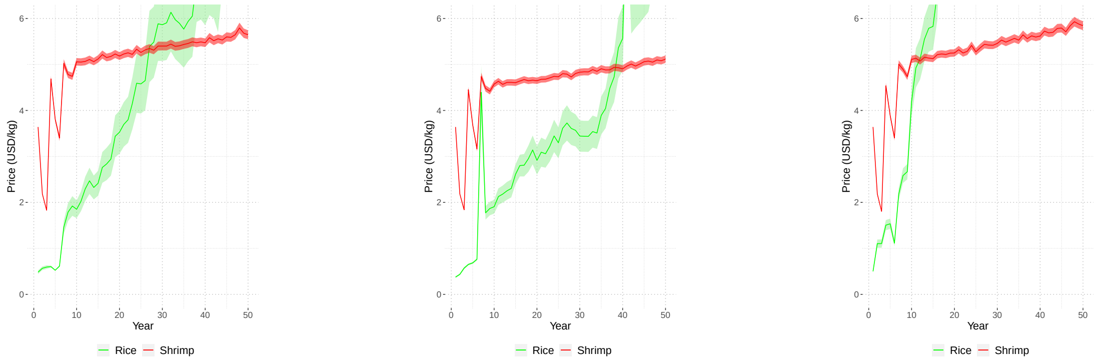
Figure 5.12: Impacts of different settings of the direct payment measure on salinity distribution (a, b, c), livelihood choices (d, e, f), crop prices (g, h, i), and profit rates (j, j, l)



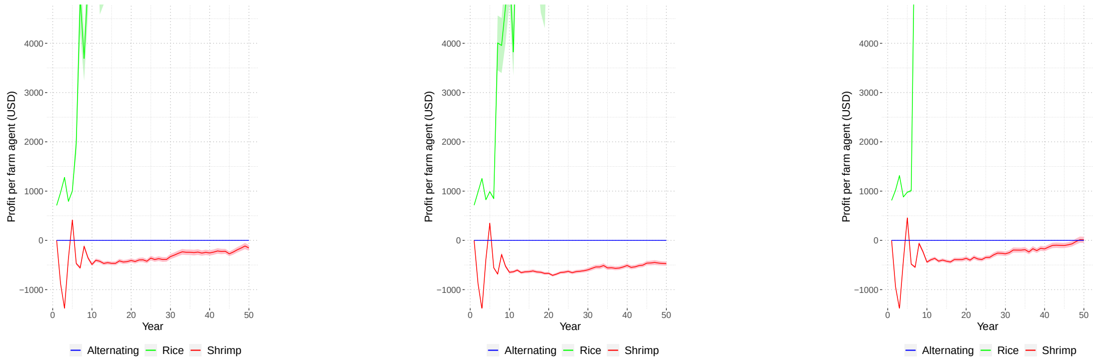
(a) 15% (b) 30% (c) 60%



(d) 15% (e) 30% (f) 60%



(g) 15% (h) 30% (i) 60%



(j) 15% (k) 30% (l) 60%

Figure 5.13: Impacts of different settings of the price support measure on salinity distribution (a, b, c), livelihood choices (d, e, f), crop prices (g, h, i), and profit rates (j, j, l)

Chapter 6

Conclusion

We developed in our thesis an ABM that emulates an economic landscape of a provincial, agricultural economy in the VMD, integrating the environmental system with two levels of the human system: the social level, which includes both the market and the government, and the individual level. The model is used to evaluate the impact of a set of measures, unofficially deemed as the rice-first measures, on the local environment, the economic interest of the people, and the food security of the region. Results obtained suggest that fully turning away from the rice-first agenda is not in the interest of the region. In the event of a severe saltwater intrusion, without certain rice-first measures, collective maladaptation could occur and lead to a worse outcome.

But not all rice-first measures are the same. The land-use planning measure has proved to be relatively effective in regulating the adaptation efforts of farmers. The direct payment measure, while able to have a positive impact, is currently not properly specified to achieve any distinguishable results. The possible inflationary pressure of the direct payment measure should also be taken into account. The price support measure is not beneficial and ought to be reconsidered.

There are limitations in our model that compromise the validity of our results. That the results are also purely qualitative is also found wanting and unable to showcase the full strength of ABM as a policy impact assessment methodology. However, we succeeded in obtaining a functional model that provided answers to our research question, acting as a “proof of concept” for the use of ABM in analysing and assessing policy impact in the VMD. The results we obtain, though hard to validate, can become the starting point for future research.

Appendix A

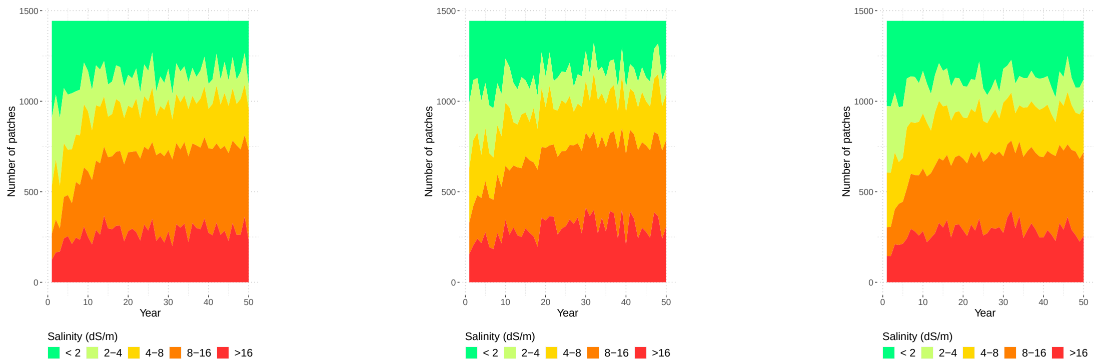
Model detail

Variable	Initial value
population	500
simulation-length	50
mean-yield-rice	6,200
mean-yield-shrimp	500
price-rice-initial	0.206
price-shrimp-initial	3.64
inputs-rice	440
inputs-shrimp	1179
labour-rice	70
labour-shrimp	153
depreciation-rice	103.88
depreciation-shrimp	300
theta	0.5
expectation-weight	0.2
productivity-rice-past	1
productivity-shrimp-past	1

Table A.1: Initial values of model parameters and variables

Appendix B

Results of the sensitivity analysis



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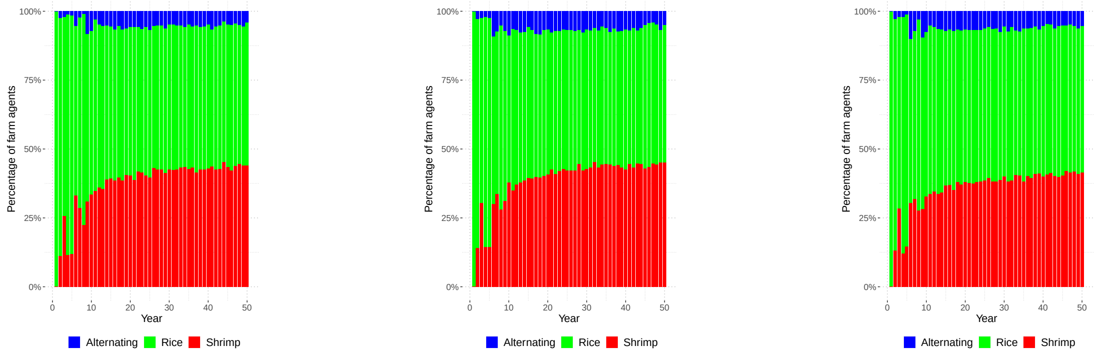
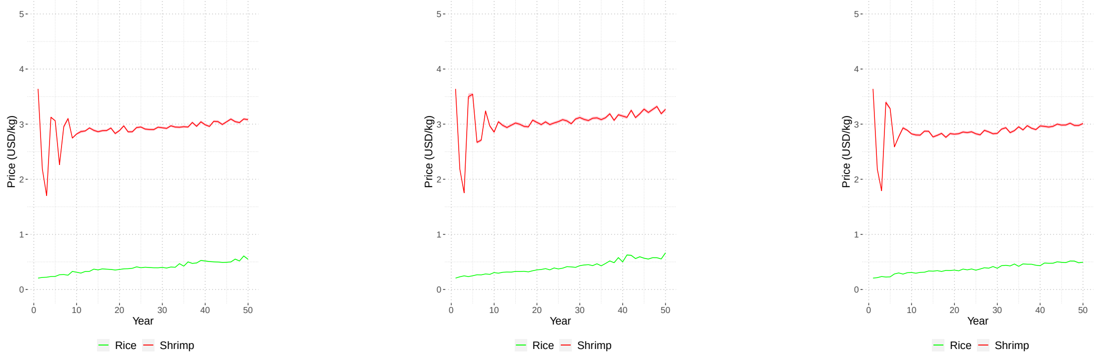


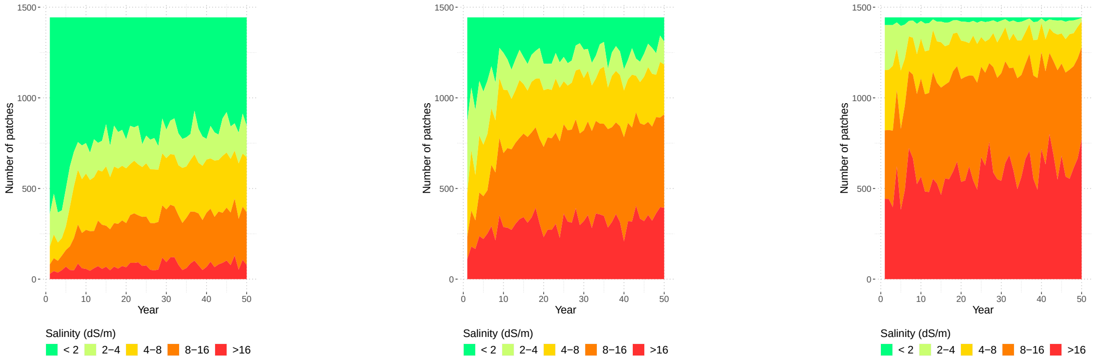
(d) $\lambda_{s,r} = 0.1$ (e) $\lambda_{s,r} = 0.45$ (f) $\lambda_{s,r} = 1$



(g) $\lambda_{s,r} = 0.1$ (h) $\lambda_{s,r} = 0.45$ (i) $\lambda_{s,r} = 1$

(j) $\lambda_{s,r} = 0.1$ (k) $\lambda_{s,r} = 0.45$ (l) $\lambda_{s,r} = 1$

Figure B.1: Results of the sensitivity analysis for $\lambda_{s,r}$



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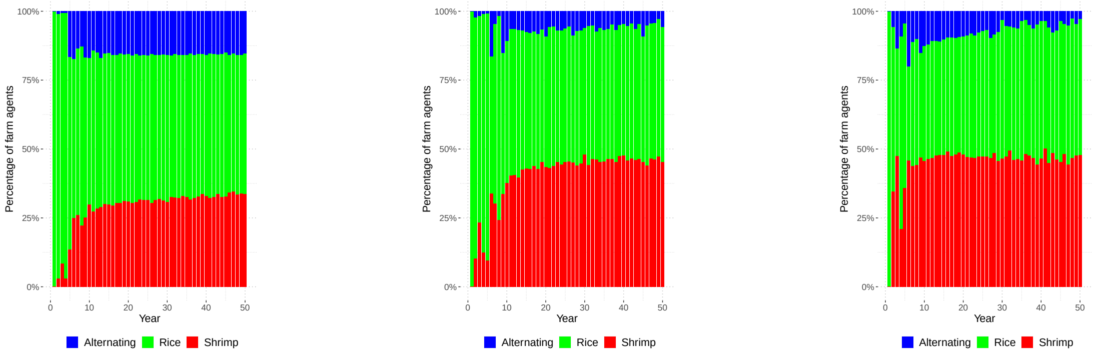
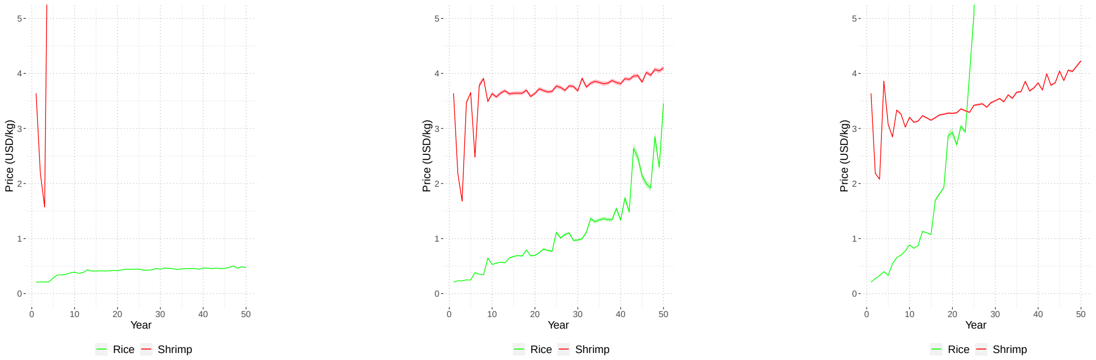


(d) $\lambda_{s,l} = 0.1$ (e) $\lambda_{s,l} = 0.45$ (f) $\lambda_{s,l} = 1$



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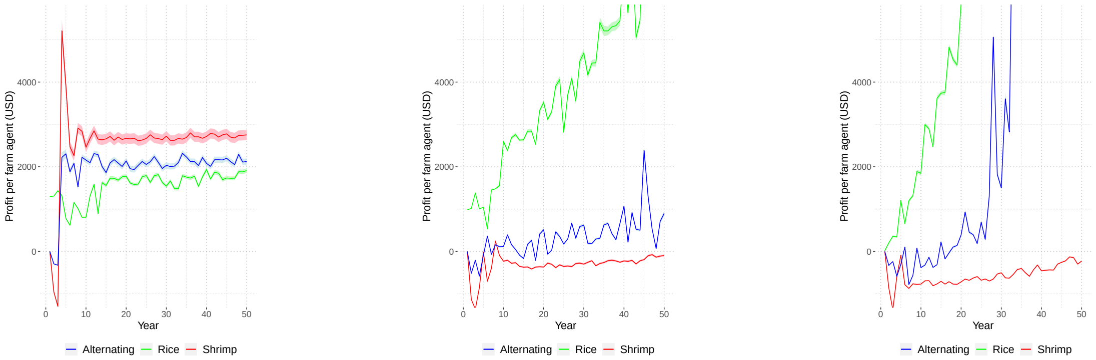
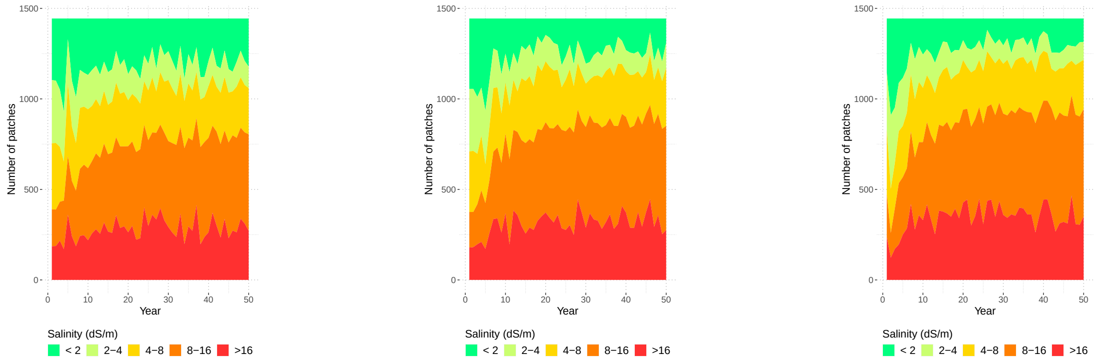


(j) $\lambda_{s,l} = 0.1$ (k) $\lambda_{s,l} = 0.45$ (l) $\lambda_{s,l} = 1$

Figure B.2: Results of the sensitivity analysis for $\lambda_{s,l}$



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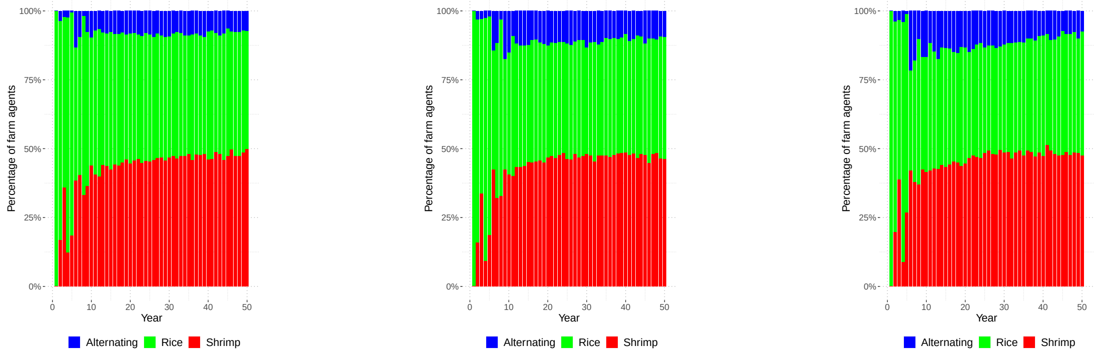

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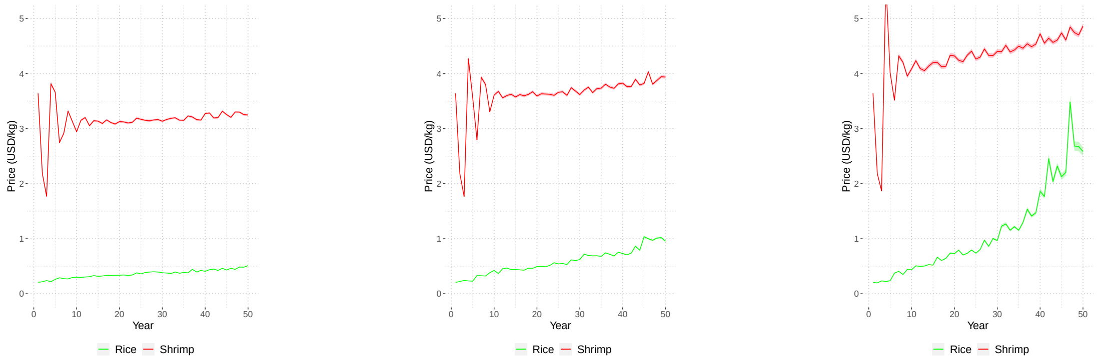
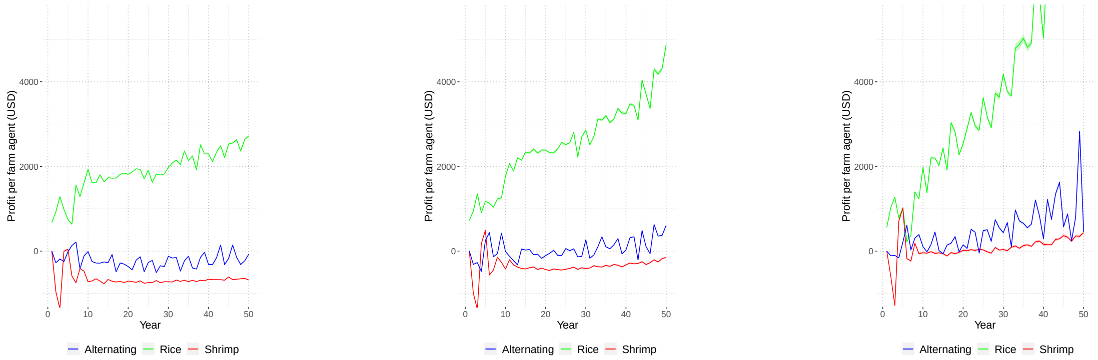
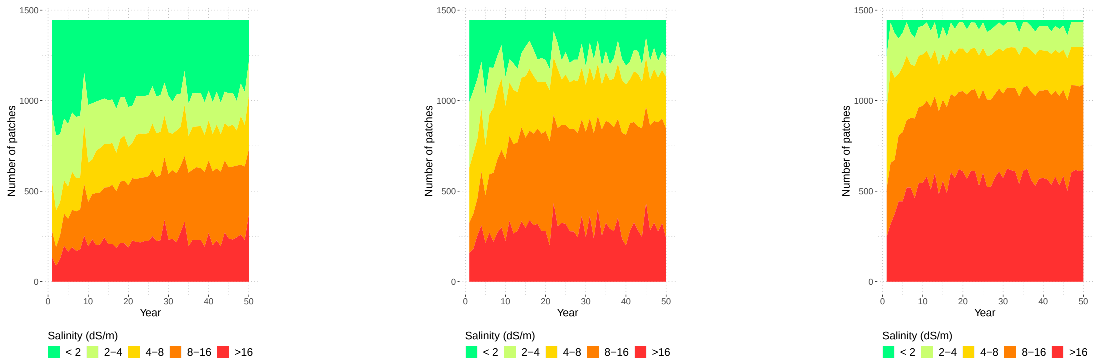


(g) $\lambda_{r,l} = 0.1$ (h) $\lambda_{r,l} = 0.4$ (i) $\lambda_{r,l} = 1$



(j) $\lambda_{r,l} = 0.1$ (k) $\lambda_{r,l} = 0.4$ (l) $\lambda_{r,l} = 1$

Figure B.3: Results of the sensitivity analysis for $\lambda_{r,l}$



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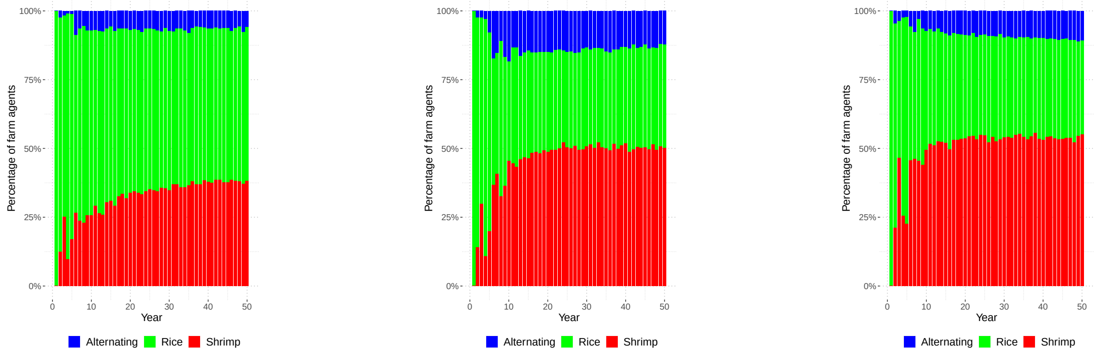

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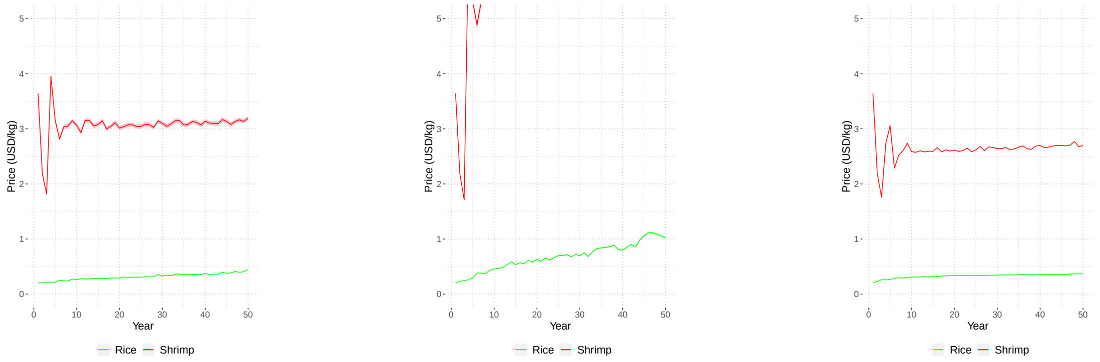

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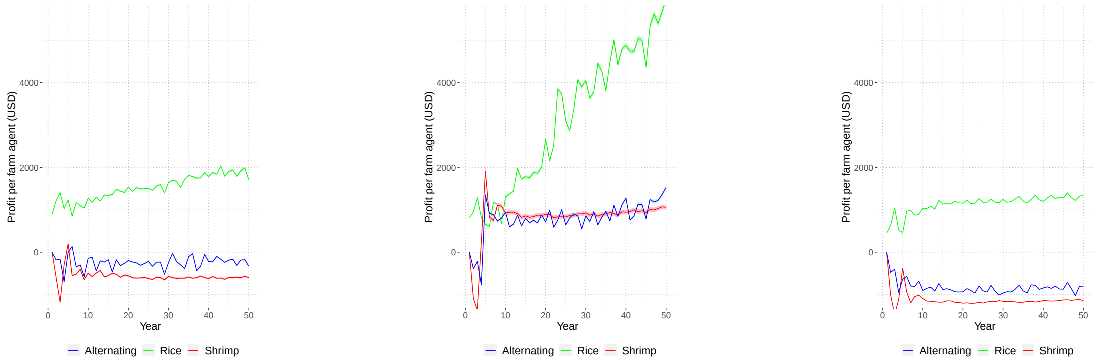
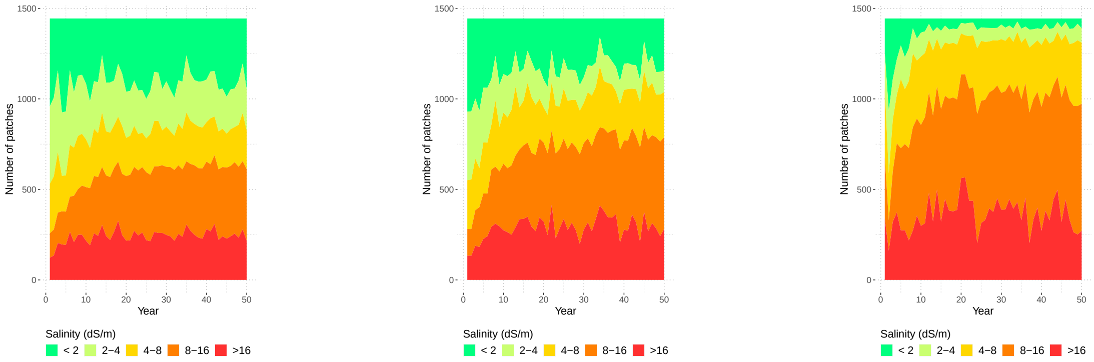


(j) $p = 0.1$ (k) $p = 0.3$ (l) $p = 0.9$

Figure B.4: Results of the sensitivity analysis for p



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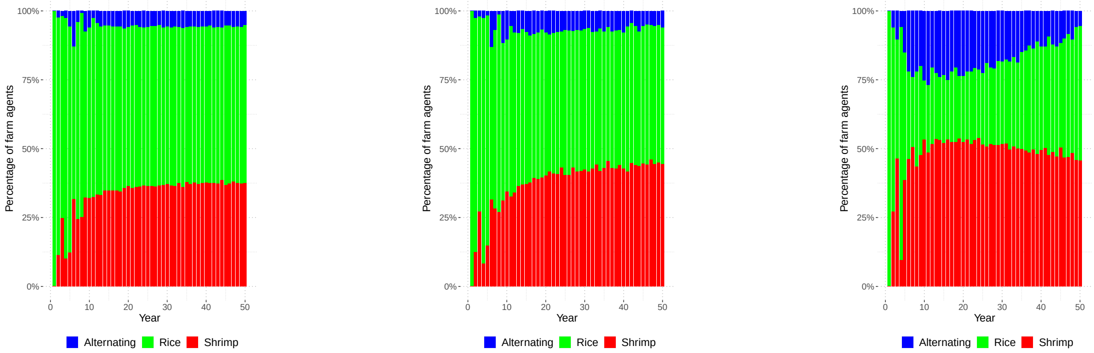

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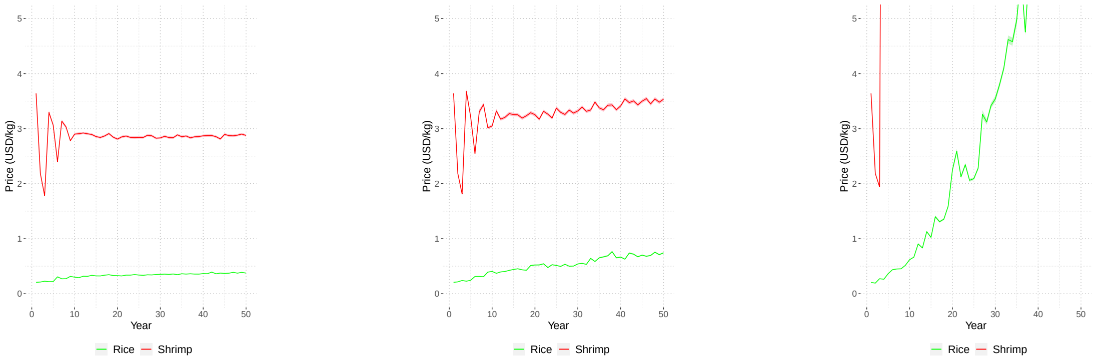
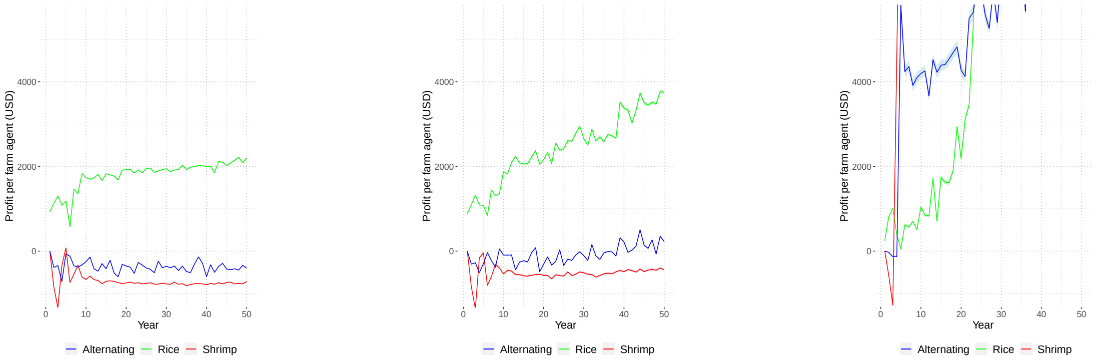
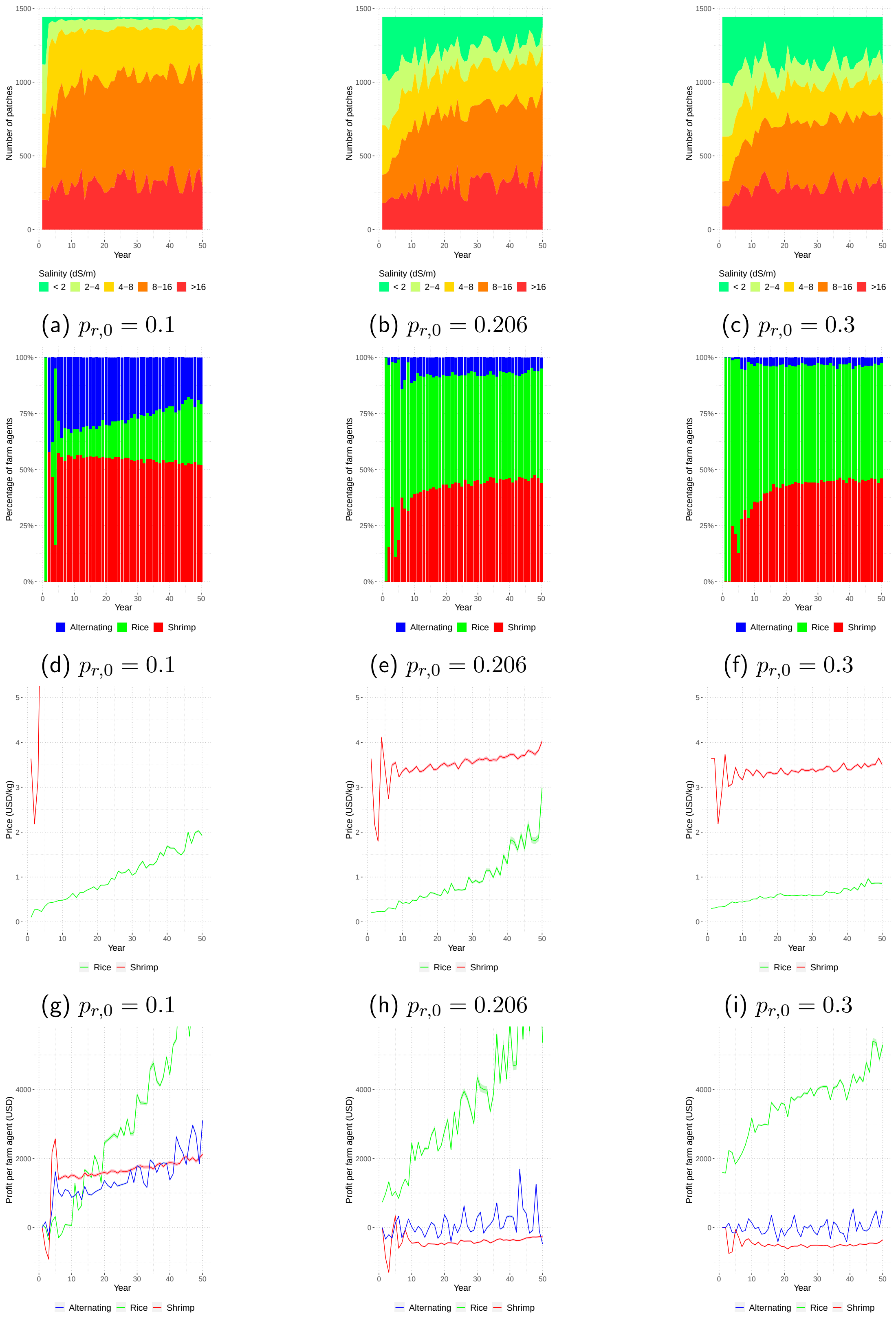


(g) $\nu = 1$ (h) $\nu = 2$ (i) $\nu = 3$



(j) $\nu = 1$ (k) $\nu = 2$ (l) $\nu = 3$

Figure B.5: Results of the sensitivity analysis for ν



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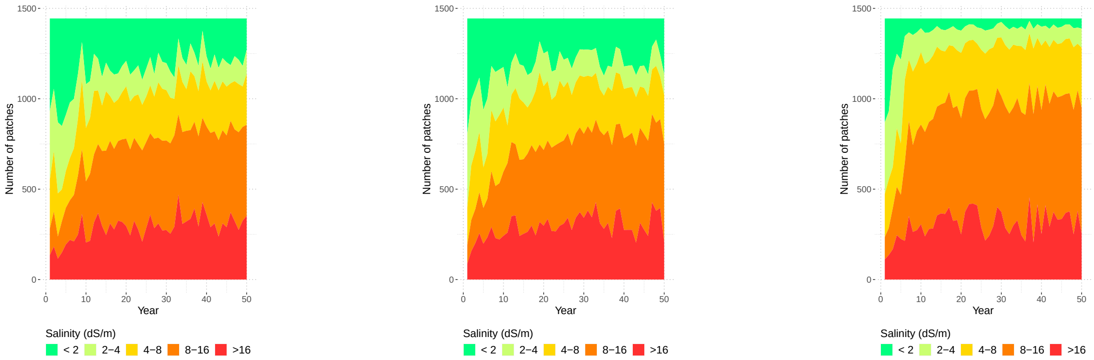
(g) $p_{r,0} = 0.1$ (h) $p_{r,0} = 0.206$ (i) $p_{r,0} = 0.3$

(j) $p_{r,0} = 0.1$ (k) $p_{r,0} = 0.206$ (l) $p_{r,0} = 0.3$

Figure B.6: Results of the sensitivity analysis for $p_{r,0}$



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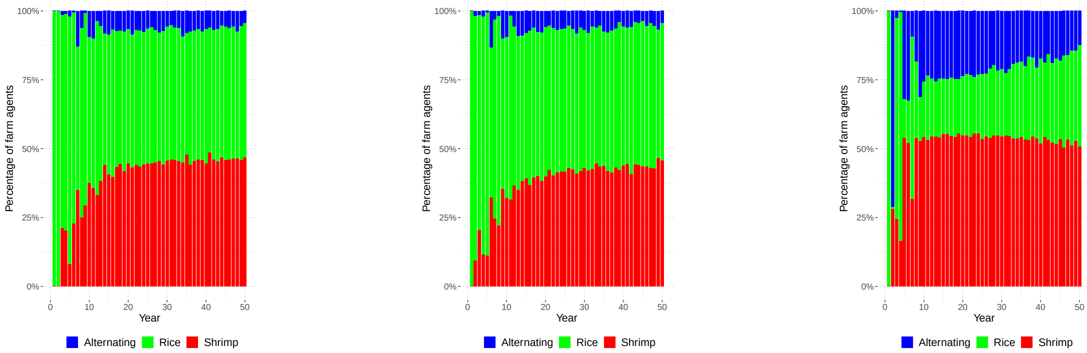

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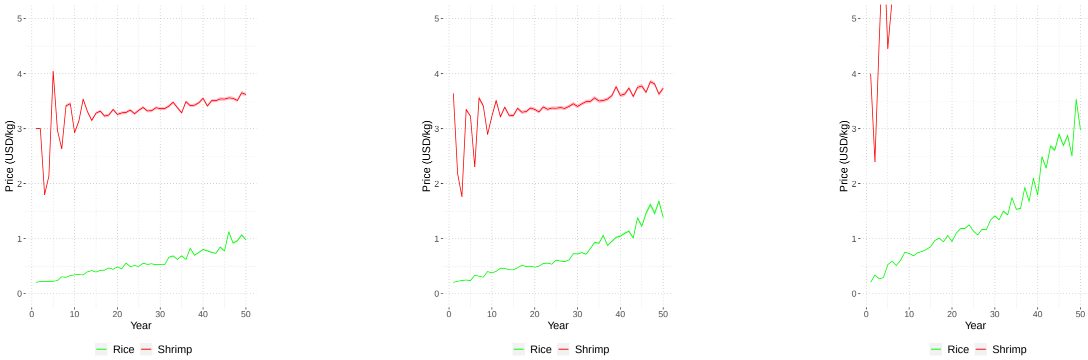
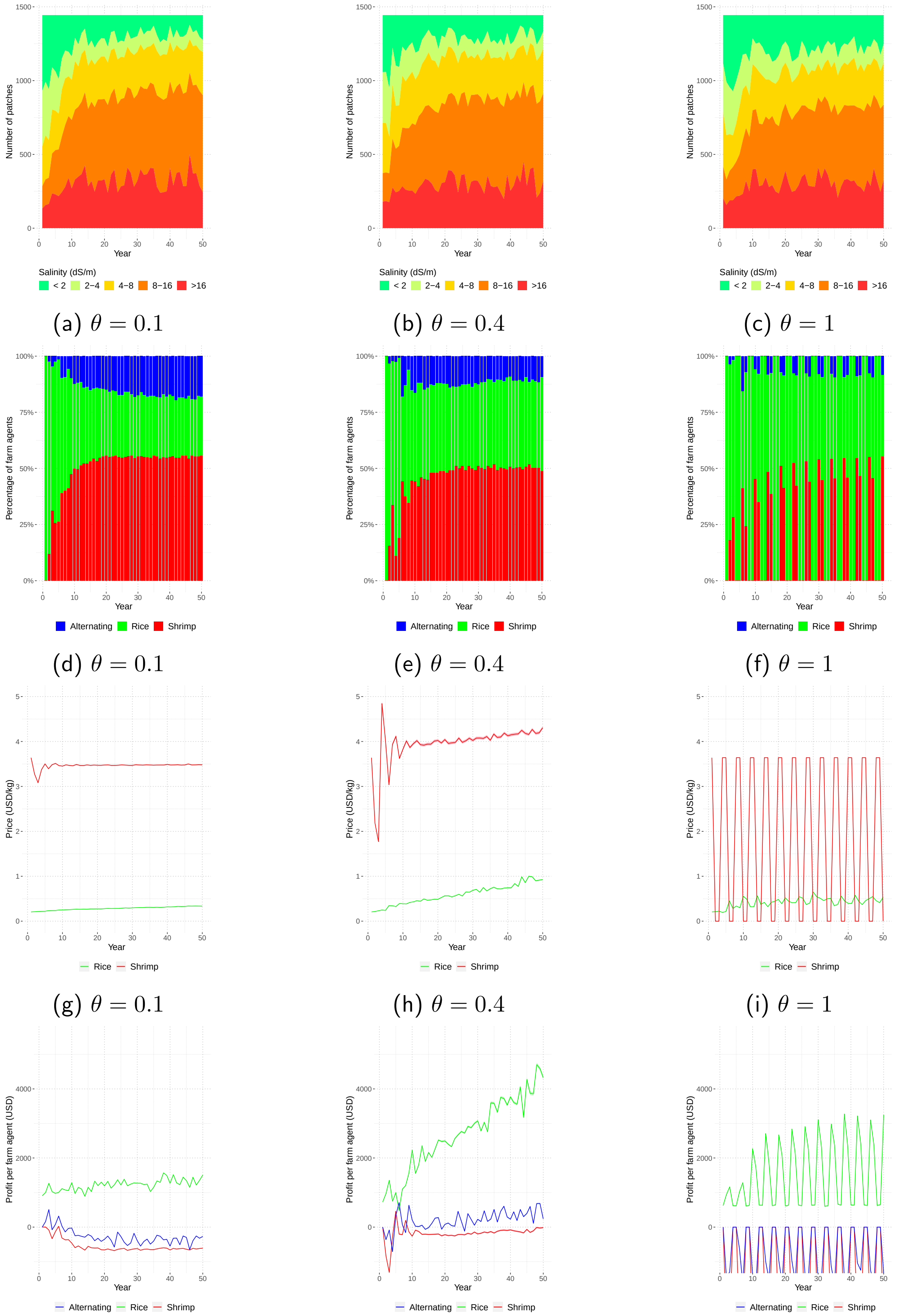


(g) $p_{s,0} = 3$ (h) $p_{s,0} = 3.64$ (i) $p_{s,0} = 4$

(j) $p_{s,0} = 3$ (k) $p_{s,0} = 3.64$ (l) $p_{s,0} = 4$

Figure B.7: Results of the sensitivity analysis for $p_{s,0}$



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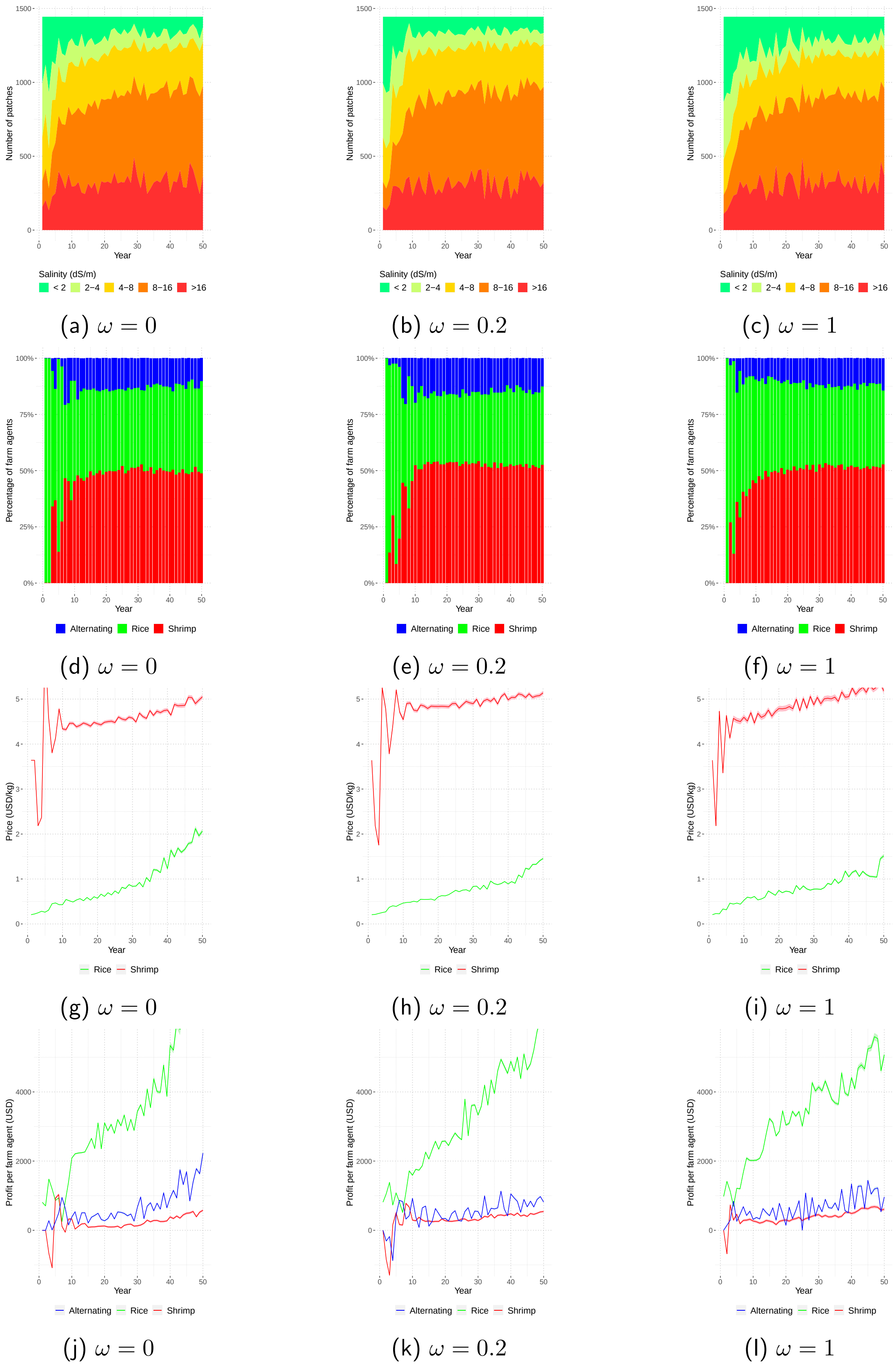
(g) $\theta = 0.1$ (h) $\theta = 0.4$ (i) $\theta = 1$

(j) $\theta = 0.1$ (k) $\theta = 0.4$ (l) $\theta = 1$

Figure B.8: Results of the sensitivity analysis for θ



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(d) $\omega = 0$ (e) $\omega = 0.2$ (f) $\omega = 1$

(g) $\omega = 0$ (h) $\omega = 0.2$ (i) $\omega = 1$

(j) $\omega = 0$ (k) $\omega = 0.2$ (l) $\omega = 1$

Figure B.9: Results of the sensitivity analysis for ω

Appendix C

Additional graphical results

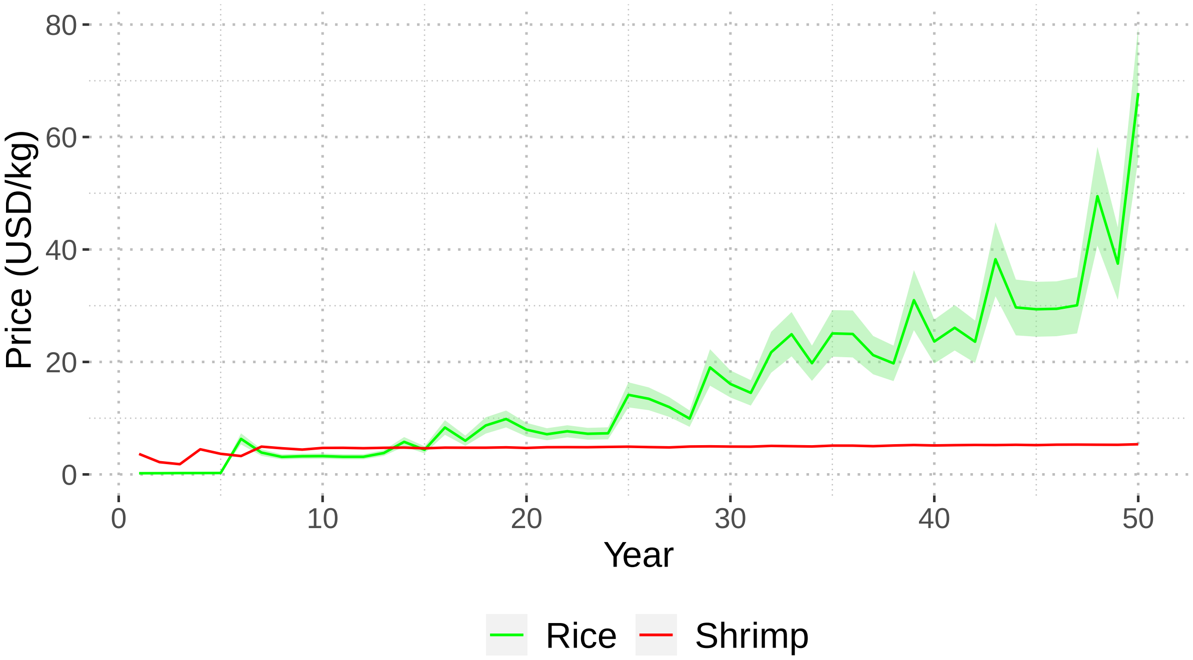


Figure C.1: Crop prices in the scenario without the rice-first agenda and with severe saltwater intrusion

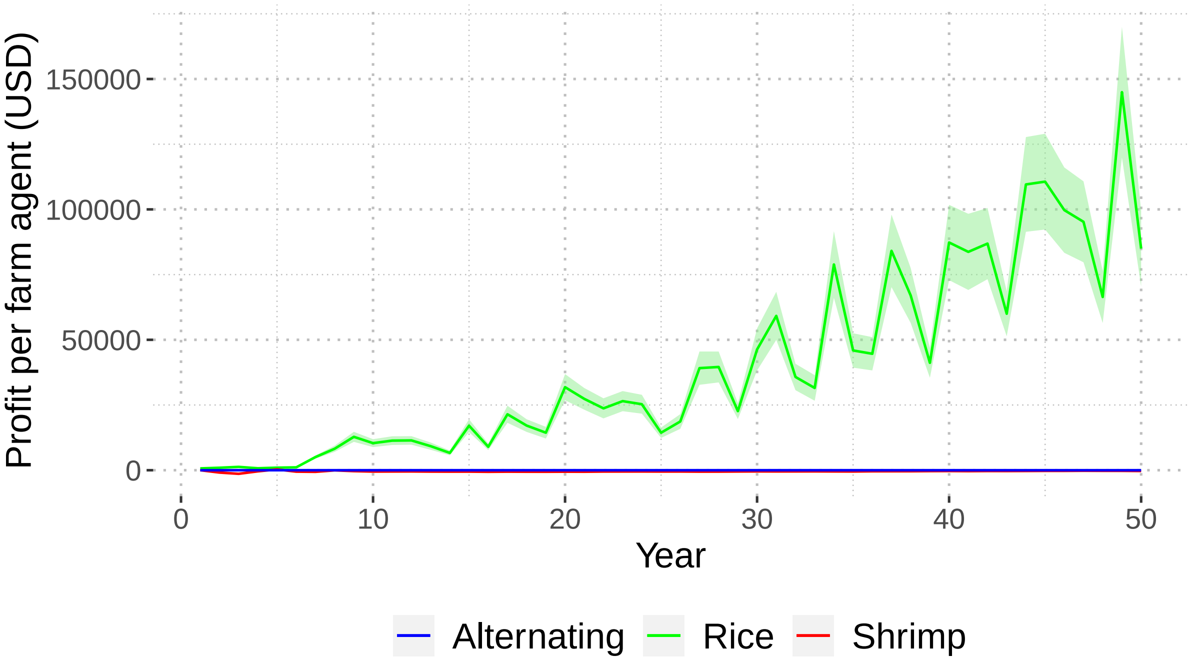
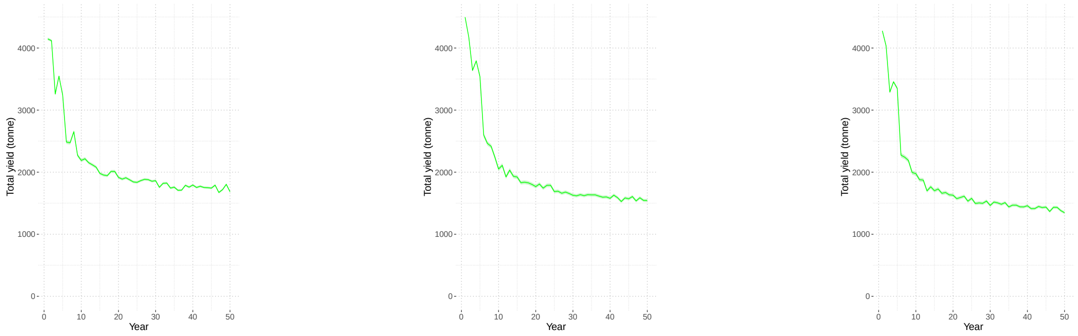
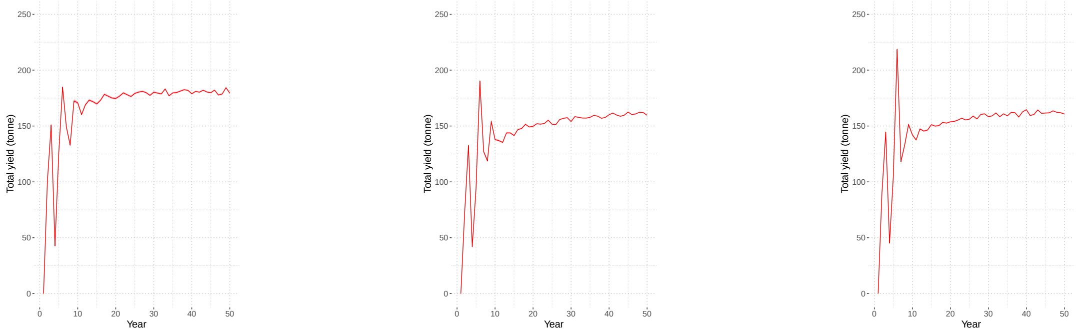


Figure C.2: Profit rates in the scenario without the rice-first agenda and with severe saltwater intrusion

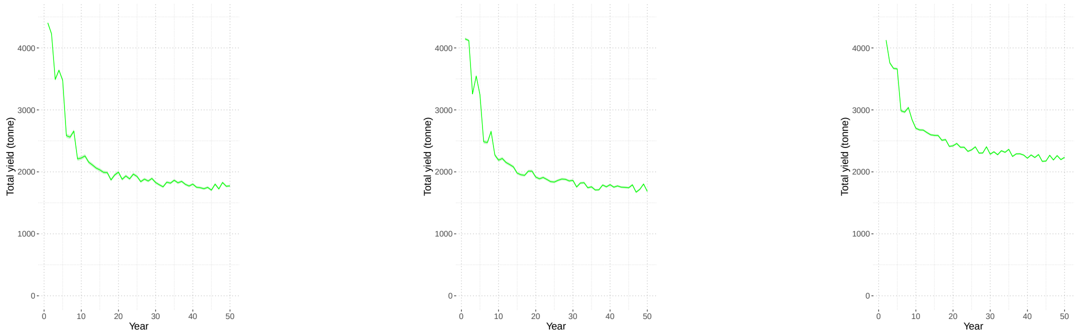


(a) Land-use planning (b) Direct payment (c) Price support

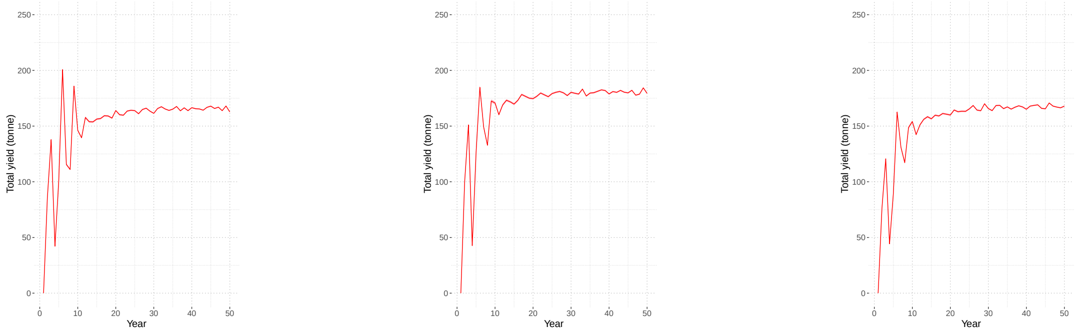


(d) Land-use planning (e) Direct payment (f) Price support

Figure C.3: Impacts of different measures
on total yield of rice (a, b, c), total yield of shrimp (d, e, f)

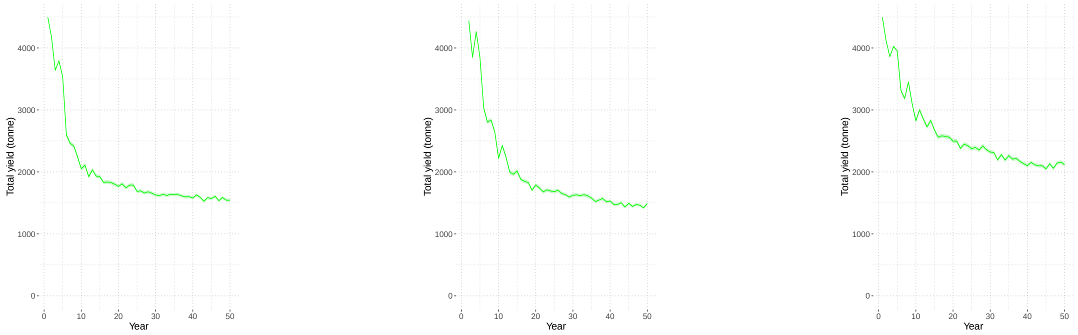


(a) 20% (b) 42% (c) 60%

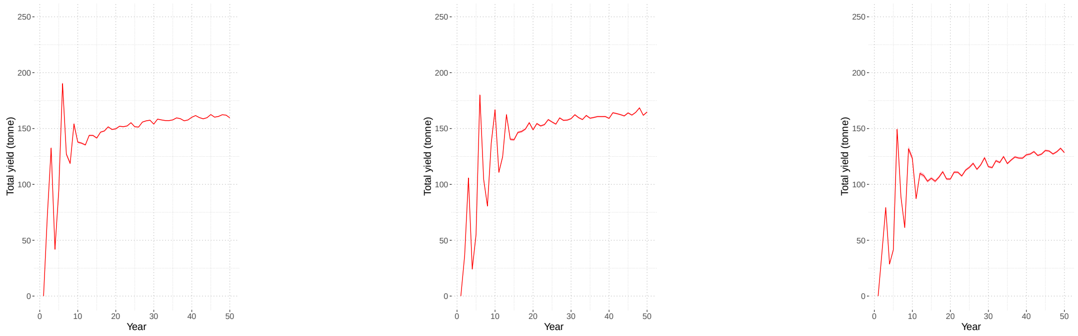


(d) 20% (e) 42% (f) 60%

Figure C.4: Impacts of different settings of the land-use planning measure on total yield of rice (a, b, c), total yield of shrimp (d, e, f)

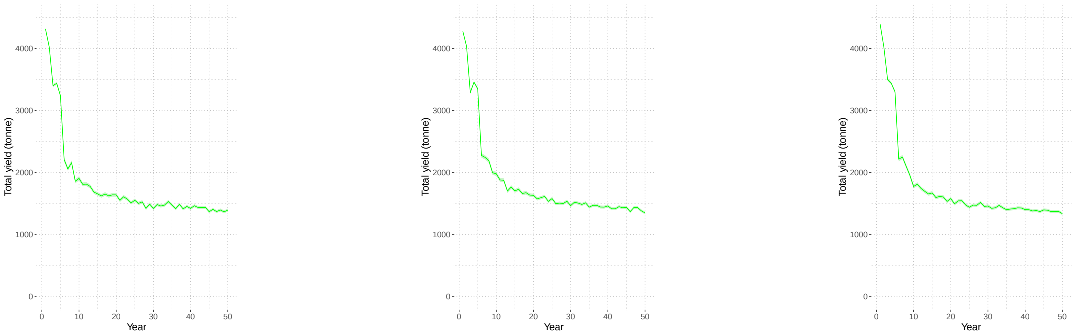


(a) 47 USD (b) 500 USD (c) 1,000 USD

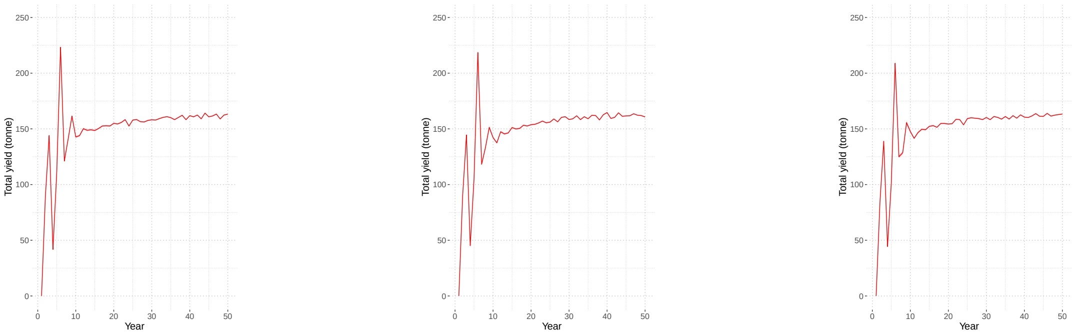


(d) 47 USD (e) 500 USD (f) 1,000 USD

Figure C.5: Impacts of different settings of the direct payment measure on total yield of rice (a, b, c), total yield of shrimp (d, e, f)



(a) 15 % (b) 30 % (c) 60 %



(d) 15 % (e) 30 % (f) 60 %

Figure C.6: Impacts of different settings of the price support measure on total yield of rice (a, b, c), total yield of shrimp (d, e, f)

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