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Part 3

LUCAS-GEMMES: Integrated dynamics of adaptation strategies in the Vietnamese Mekong Delta

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Abstract

The predominantly agricultural Mekong Delta region will be profoundly affected by the effects of climate change, such as rising temperatures, sea level rise, and salinization. But recent studies show that other factors, such as sand mining and groundwater exploitation, will also largely contribute to future pressures, particularly through land subsidence. Alongside the fight against climate change, this makes it necessary to design strategies and policies for subsidence mitigation, not only at the individual level (mainly farmers), but also at the institutional level (province and region). Indeed, in the Vietnamese Mekong Delta (VMD), local provinces play a crucial role in the choice and implementation of strategies for the exploitation of natural resources, such as water or sand. However, the VMD is also a complex system in which the decisions of one province can have indirect effects on the other 12 provinces, especially because some provinces share common agro-ecological regions and aquifer areas.

This chapter aims to explore, through simulation of an integrated model, the economic impact on farmers of the adaptation strategies chosen by the provinces under a number of climatic and economic scenarios. It thus builds on the adaptation options evaluated in Part 3 of the report. In particular, one objective is to understand which conditions of inter-province coordination on groundwater exploitation in common agro-ecological areas could improve the economic situation of farmers. To this end, the LUCAS model (an agent-based model for land-use change adaptation strategies in the context of climate change) [Truong *et al.*, 2021] was extended to take groundwater use by farmers into account, as well as the subsidence dynamics and macroeconomic trends from the GEMMES model. In the updated model, called LUCAS-GEMMES, subsidence-related adaptation strategies chosen at the provincial level and their interactions with individual decisions were also introduced.

The simulation is performed with 4 experiments including (i) No provincial adaptation strategies and ignorance of subsidence dynamics; (ii) No adaptation strategies while subsidence impacts the benefit of land-use production; (iii) Individual adaptation strategies combined with the impact of subsidence; (iv) Province and individual adaptation combined with the impact of subsidence.

The results show that decisions in early response to low-level subsidence bring many positive results in resource management, such as significantly reducing water use in the dry season, and reducing the vulnerability area from subsidence and climate change. The results also show a decrease in incomes in case of adaptation. Therefore, it is necessary to have investment solutions (technical support in shrimp farming, studying for new upland crops in the dry season) for new land-use types that could compensate for the economic benefits lost when applying policies that restrict people in the use of resources.

Tóm tắt

Đồng bằng sông Cửu Long (ĐBSCL) là vùng sản xuất lương thực chủ yếu của Việt Nam sẽ bị ảnh hưởng rất lớn bởi tác động của biến đổi khí hậu như nhiệt độ tăng, nước biển dâng, xâm nhập mặn. Tuy nhiên các nghiên cứu gần đây cho thấy rằng các yếu tố khác như khai thác cát và khai thác nước ngầm cũng sẽ góp phần vào những tác động này, đặc biệt là do sụt lún đất. Bên cạnh cuộc chiến chống biến đổi khí hậu, cần có chiến lược và chính sách để giảm thiểu sụt lún không chỉ ở người dân (chủ yếu là nông dân) mà còn cần chính sách của nhà nước (tỉnh và cả vùng). Ở Việt Nam nói chung và ĐBSCL nói riêng, cấp tỉnh đóng một vai trò quan trọng trong việc xây dựng chính sách cụ thể và quản lý trong khai thác tài nguyên thiên nhiên bao gồm nước ngầm và cát trên sông. Tuy nhiên, nguồn tài nguyên là một hệ thống phức tạp của cả vùng, do đó quyết định của một tỉnh có thể có tác động gián tiếp đến 12 tỉnh khác, đặc biệt đối với một số tỉnh có chung các vùng sinh thái nông nghiệp và các vùng chứa nước ngầm. Chương sách này nhằm mục đích ứng dụng mô hình trong đánh giá tổng hợp tác động của các chiến lược thích ứng do các tỉnh lựa chọn đến các mặt kinh tế, sử dụng đất và nước của người dân trong một số kịch bản biến đổi khí hậu và kinh tế. Do đó, chương sách được xây dựng dựa trên các giải pháp thích ứng đã được đánh giá trong Phần 3 của báo cáo. Đặc biệt, một trong những mục tiêu là xem xét sự phối hợp giữa các tỉnh trong việc khai thác nước ngầm trong các vùng sinh thái nông nghiệp chung như thế nào để cải thiện kinh tế của người dân. Vì vậy, mô hình LUCAS (Mô hình dựa trên tác nhân cho các chiến lược sử dụng đất thích ứng trong bối cảnh biến đổi khí hậu) [Truong *et al.*, 2021] đã được mở rộng để tính đến việc sử dụng nước ngầm của nông dân, cũng như tác động của sụt lún và xu hướng kinh tế vĩ mô từ mô hình GEMMES. Mô hình LUCAS được cập nhật với tên gọi là LUCAS-GEMMES cho phép nghiên cứu các chiến lược thích ứng biến đổi khí hậu kết hợp với hạn chế sụt lún ở cấp tỉnh với các quyết định sử dụng đất của người dân. Mô phỏng được thực hiện với 4 thực nghiệm máy tính bao gồm (i) Không áp dụng chiến lược thích ứng cấp tỉnh và sự thiếu hiểu biết của việc không đưa sụt lún vào quyết định sử dụng đất; (ii) Không có chiến lược thích ứng trong khi sụt lún ảnh hưởng đến sản xuất nông nghiệp; (iii) Áp dụng các chiến lược thích ứng riêng lẻ dưới tác động của sụt lún; (iv) Sự thích ứng của từng tỉnh và từng cá nhân dưới tác động của sụt lún. Kết quả cho thấy các quyết định ứng phó sớm với sụt lún ở mức độ thấp mang lại nhiều kết quả tích cực trong quản lý tài nguyên như giảm đáng kể lượng nước sử dụng trong mùa khô và theo đó giảm khu vực dễ bị tổn thương do sụt lún và biến đổi khí hậu. Kết quả cũng cho thấy thu nhập từ hoạt động nông nghiệp giảm trong trường hợp thích nghi. Do đó, cần có các giải pháp đầu tư (hỗ trợ kỹ thuật nuôi tôm, nghiên cứu các loại cây trồng cạn mới trong mùa khô) cho các loại hình sử dụng đất mới nhằm bù đắp lợi ích kinh tế bị mất khi áp dụng các chính sách hạn chế người dân sử dụng tài nguyên.

Résumé

La région du delta du Mékong, essentiellement agricole, sera profondément touchée par les effets du changement climatique, tels que la hausse des températures, l'élévation du niveau de la mer et la salinisation. Mais des études récentes montrent que d'autres facteurs, comme l'extraction de sable et l'exploitation des eaux souterraines, contribueront également fortement aux pressions futures, notamment par la subsidence. Au-delà de la lutte contre le changement climatique, il est donc nécessaire de concevoir des stratégies et des politiques d'atténuation de la subsidence, non seulement au niveau individuel (principalement les agriculteurs), mais aussi au niveau institutionnel (province et région). En effet, dans le delta du Mékong vietnamien (DMV), les provinces locales jouent un rôle crucial dans le choix et la mise en œuvre des stratégies d'exploitation des ressources naturelles, comme l'eau ou le sable. Cependant, le DMV est aussi un système complexe dans lequel les décisions d'une province peuvent avoir des effets indirects sur les 12 autres provinces, notamment parce que certaines provinces partagent des régions agro-écologiques et des zones aquifères communes.

Ce chapitre vise à explorer, par la simulation d'un modèle intégré, l'impact économique sur les agriculteurs des stratégies d'adaptation choisies par les provinces dans un certain nombre de scénarios climatiques et économiques. Il s'appuie donc sur les options d'adaptation évaluées dans la [partie 3](#) du rapport. En particulier, un objectif est de comprendre dans quelles conditions de coordination entre les provinces sur l'exploitation des eaux souterraines, dans des zones agro-écologiques communes, la situation économique des agriculteurs peut s'améliorer. À cette fin, le modèle LUCAS (un modèle "basé agents" pour les stratégies d'adaptation au changement d'utilisation des terres dans le contexte du changement climatique) [Truong *et al.*, 2021] a été étendu pour prendre en compte l'utilisation des eaux souterraines par les agriculteurs, ainsi que la dynamique de subsidence et les tendances macroéconomiques du modèle GEMMES. Dans le modèle mis à jour, appelé LUCAS-GEMMES, les stratégies d'adaptation liées à la subsidence choisies au niveau provincial et leurs interactions avec les décisions individuelles ont également été introduites.

La simulation est réalisée à l'aide de quatre expériences : (i) aucune stratégie d'adaptation provinciale et ignorance de la dynamique de la subsidence ; (ii) aucune stratégie d'adaptation alors que la subsidence a un impact sur le bénéfice de la production de l'utilisation des terres ; (iii) stratégies d'adaptation individuelles combinées à l'impact de la subsidence ; (iv) adaptation provinciale et individuelle combinée à l'impact de la subsidence.

Les résultats montrent que les décisions prises en réponse précoce à un affaissement de faible niveau apportent de nombreux résultats positifs dans la gestion des ressources, tels que la réduction significative de l'utilisation de l'eau pendant la saison sèche, puis la réduction de la zone de vulnérabilité à la subsidence et au changement climatique. Les résultats

montrent également une diminution des revenus en cas d'adaptation. Par conséquent, il est nécessaire d'avoir des solutions d'investissement (soutien technique dans l'élevage de crevettes, étude de nouvelles cultures de montagne en saison sèche) pour de nouveaux types d'utilisation des terres qui compenseraient les avantages économiques perdus lors de l'application de politiques qui limitent les personnes dans l'utilisation des ressources.

1. Introduction

The Vietnamese Mekong Delta (VMD) is increasingly exposed to climate and environmental changes, triggered by both global climate change and anthropogenic activities in the Delta or upstream in the Mekong River basin: rising temperatures, precipitation changes, increasing saline water intrusions, decreased availability of freshwater (see Part 2, this report, and GEMMES COP26 report [Espagne *et al.*, 2021b]). This is already severely affecting agriculture and aquaculture, which are the main activities in the VMD. Groundwater extraction, which has partially compensated for this vulnerability and enabled the agricultural intensification policy implemented since the 2000s to continue, is in fact worsening the situation by increasing subsidence throughout the Delta [Minderhoud *et al.*, 2020], and hence increasing the risk that large portions of the Delta fall below sea-level within decades.

Although this corpus of solid scientific evidence has only recently surfaced, general awareness of this state of affairs is not new, and many initiatives have begun to be undertaken [Government of Viet Nam, 2018] – especially at provincial level – as to whether or not to authorize the use of groundwater depending on the state of the aquifer zones, to facilitate the construction of retention basins [MONRE, 2017], or to reduce crops that are excessively freshwater-intensive at certain seasons (see Focus 4, this report). However, these initiatives face two major obstacles that severely limit their scope and effectiveness, stemming from the fact that the political division into provinces does not necessarily reflect groundwater resources: some provinces may be located at the confluence of extremely different agro-ecological zones, making it difficult to design a single policy

for the whole province; conversely, several provinces may share the same agro-ecological zone, ideally requiring concerted policies of groundwater exploitation to be implemented.

The objective of this chapter is to explore – using repeated simulations of a large-scale integrated agent-based model – which combinations of province-level policies and individual adaptation strategies appear to be sustainable, under a number of climate change and subsidence scenarios. In particular, we are interested in understanding the impact of different forms of coordination (or lack thereof) between actors in the system on the system's overall sustainability, as expressed in terms of average farmer income and debts. In [Truong *et al.*, 2021], a first version of the model called LUCAS was introduced; farmers play the key role, basically driving all the dynamics of the model by individually selecting appropriate land-use types for their plot. This first version aimed to reproduce the distribution of land-use in the Vietnamese Mekong Delta, and to understand the impact of various climate scenarios (e.g. changes in temperature and rainfall) on this distribution. The provinces were represented as agents in the model, but their role was limited to providing, or restricting, funding for farmers' adaptation strategies.

The extension of LUCAS (named LUCAS-GEMMES) presented and explored in this chapter reinforces the economic dimension of the model, by allowing farmers to take out loans to invest in land-use changes beyond their initial financial capacity. More importantly, it strengthens the ability of provinces to influence individual adaptation strategies, according to the agro-ecological zone for which they are responsible and the level of subsidence measured: policies available to

provinces can include prohibiting certain land-uses in order to limit or even prevent water pumping. The subsidence thresholds at which these policies are triggered, and the coordination between provinces in choosing these thresholds, are among the elements whose importance and relevance we wish to measure in order to provide concrete recommendations. LUCAS-GEMMES, presented in detail in Section 3, therefore allows modelers to explore various combinations of joint or coordinated decisions at the scale of provinces. A number of experiments are carried out and presented in Section 4, detailing the interactions and feedback between provinces and farmers' decision-making processes in a number of scenarios, and allowing conclusions to be drawn as to which strategies, in terms of financial facilities and coordination between provinces, appear to be the most sustainable at the scale of the VMD.

2. Context

2.1 Institutional management of Climate Change in the Vietnamese Mekong Delta

The Vietnamese Mekong Delta is classified into 3 ecological zones (see Figure 3.3) that provide specific properties for agricultural development [Government of Viet Nam, 2017]. The Upstream zone, located in the upstream part of the Delta, has freshwater but also floods during the rainy season; it covers the provinces and cities of An Giang, Dong Thap, Long An and part of the provinces of Kien Giang and Can Tho. The Middle zone, located in the central part of the Delta, is the transitional area between freshwater and brackish wa-

ter; it includes part of Can Tho and Kien Giang, Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, Tien Giang, and Long An provinces. The Coastal zone is occupied by saltwater and brackish water; it covers the coastal parts of Kien Giang and Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, Ben Tre, Tien Giang, and Long An provinces.

Regarding the general policies of the Government for the region, Resolution 120/2017 [Government of Viet Nam, 2017] is an extremely important document that guides the general strategies for the Delta in response to climate change (see Part 2, this report). This resolution proposed the development of specific agricultural policies for the environment in which they are applied, and in particular the AgroEcological Zones (AEZ). In addition, Decision 324/QD-TTg [Prime Minister of Viet Nam, 2020] detailed the policies of the government for the sustainable development of the Vietnamese Mekong Delta conducted by Resolution 120. It states that the agricultural development of the Delta will be based on 3 agro-ecological zones depending on land suitability and product market. The Decision guided land-use change policies, especially in areas vulnerable to floods, droughts, and saline water intrusion; the main purpose is to change the focus of the Delta from rice production to aquaculture - fruit - rice.

Recently, Decision 287/QD-TTg [Prime Minister of Viet Nam, 2022] has provided planning solutions for the development of the Vietnamese Mekong Delta region for the 2021–2030 period, with a perspective towards 2050; the Prime Minister of Viet Nam oriented the agricultural production structure to adapt to natural condition changes in the three zones:

- The Upstream zone is a key area specialized in producing rice, freshwater aquatic products

and fruits. The area should create a diversified, modern and sustainable agriculture, taking adaptation to extreme flooding into account, and playing its role in regulating, managing and absorbing floods for the Vietnamese Mekong Delta.

– The Middle zone is identified as the main area for crop rotations involving rice and vegetables, and for the monofarming of brackish-water aquatic products, depending on seasonal water conditions.

– The Coastal zone should focus on developing saltwater or saltwater - brackish water aquaculture, fishing, on restoring and developing coastal mangrove forests, as well as protecting biodiversity and coastal strips. It should also develop an integrated agro-forestry production system, applying the principle that ecological and organic farming practices should be combined with eco-tourism activities. Finally it should proactively prevent, avoid, and reduce risks of natural disaster, climate change and sea level rise.

Driven by Government laws and documents for the Vietnamese Mekong Delta (see Part 2), the LUCAS-GEMMES model aims to demonstrate a means of testing possible adaptation strategies in terms of supporting land-use plans in the context of climate change. Many studies have shown that policies play a very important role in land-use decisions and land-use changes, but there is a lack of tools to help decision-makers include these factors in the land-use change model. In this study, we convert the policies of provinces into adaptation strategies for the chosen provinces, depending on their agro-ecology; to do so, we defined a list of the land-use types supported by the law (Decision 324/QD-TTg 2020, 287/QD-TTg 2022), based on the properties of the AEZ. The policy profile

can be adjusted depending on the case under study. It is important that provinces know how to react to different subsidence scenarios, depending on the types of cooperation.

2.2 The LUCAS model

The LUCAS (Land-Use Change for Adaptation Strategies) model [Truong *et al.*, 2021] is a spatially-explicit agent-based model [Bona-beau, 2002], designed as a virtual laboratory – at the scale of the Vietnamese Mekong Delta – to simulate and evaluate the performance of different adaptation strategies and their combinations, at different levels, in different climatic, demographic or economic scenarios. The main entities modeled as agents are the farmers, who have to make decisions concerning the type of land-use to implement for their agricultural parcels: their decision is firstly based on individual criteria (such as profitability, land suitability, capacity for conversion to other land-uses, and influence of other farmers). Then an adaptation strategy is applied depending on the risk exposure of each parcel toward temperature, precipitation, and salinity evolution.

Three simple strategies have been presented and evaluated by [Truong *et al.*, 2021] in the framework of the climate scenario RCP 8.5: the first one is based only on individual farmers' choices (they seek an appropriate land-use to eliminate risks), without any help or hindrance from the government; the second one is based only on governmental decisions (attempting to eliminate the risk by improving infrastructure such as dykes, sluice gates etc., or by financially supporting farmer adaptations), without spontaneous adaptation by farmers; and the third one is based on a combination of these two approaches, in which the

government supports the individual choices that seem relevant to reducing the impacts of climate change. Unsurprisingly, the latter is measured as the most beneficial for all actors in the system, and appears to be an interesting way to think about and develop feasible adaptation plans.

The LUCAS model offers a proof of concept framework that should make it possible, in future, to explore and compare different combinations of adaptation policies that reconcile bottom-up and top-down dynamics. Nevertheless, by focusing only on environmental changes directly linked to climate change (temperature, precipitation, global sea-level rise), it omits many other very important ones, particularly the strong future impact of land subsidence. Finally, indicators of the models were limited to land-use evolution and distribution, without investigating closely-related economic indicators. These two main aspects are the core improvements provided by the LUCAS-GEMMES model.

3. LUCAS-GEMMES model

The LUCAS-GEMMES model presented in this chapter is an extension of the LUCAS model [Truong *et al.*, 2021], incorporating some of the results of the GEMMES project in terms of subsidence and macroeconomics trends. Adaptation strategies of each province are now spatially heterogeneous (depending on the AEZ and the subsidence of the area). The economic model of farmers' agents now integrates the interest rate dynamics of the GEMMES model. Finally, key indicators are debt and benefits for farmers.

3.1 Overview

Purpose of the model

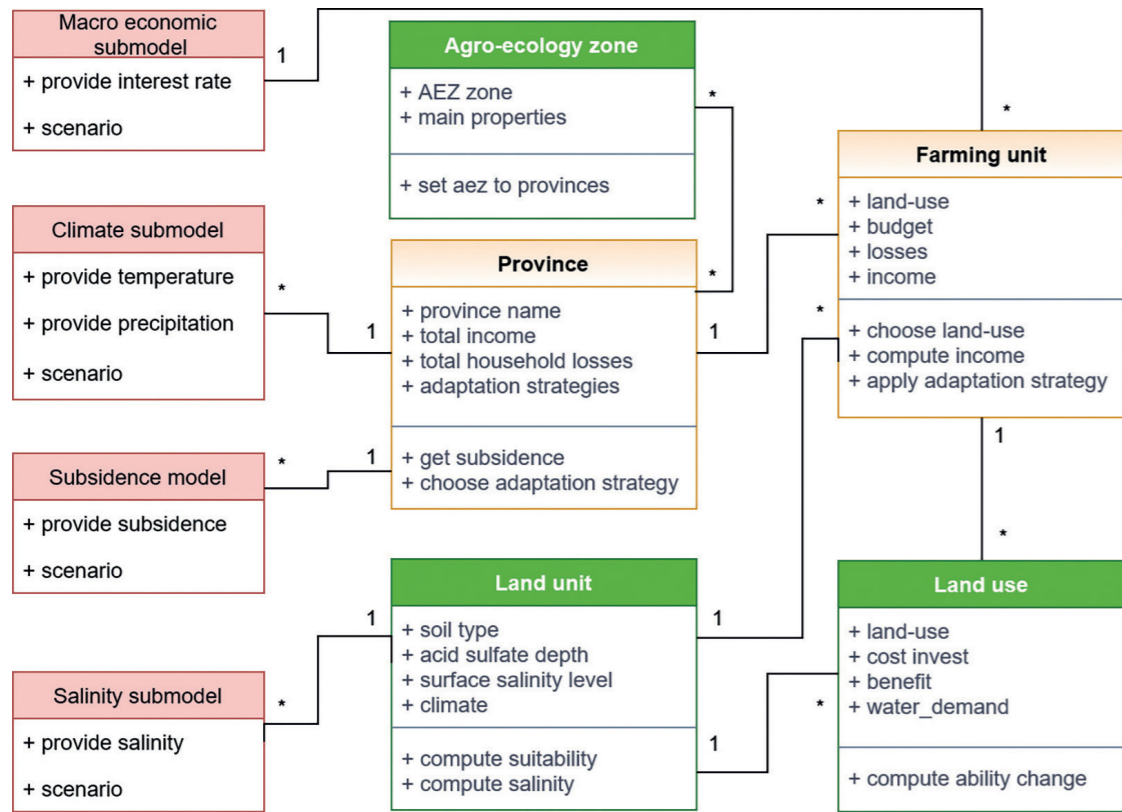
The objective of the model is to investigate spatially heterogeneous adaptation strategies of provinces in the Vietnamese Mekong Delta (taking subsidence and AEZ into account), in terms of water pumping and in interaction with farmers' land-use change decisions, in the context of climate change. For this purpose, coordinated/uncoordinated decisions among provinces will be explored.

Entities, state variables, and scale

The static description of agent types composing the model is provided in Figure 3.1 (see Online Supplementary Material for details). The model consists of 2 types of pro-active agent types that can make decisions at each simulation step: the *farming units* and the *provinces*. In addition, it contains two types of passive entities which are spatially located: the *agro-ecological zone* (AEZ) provides properties for different types of agriculture activities and the *land unit* provides detailed properties of soil texture, soil constraint water, and salinity. Finally, the model is completed with a non-spatial entity: the *land-use* provides information about the various land-use characteristics. In this model, we limit ourselves to the six dominant land-uses of the VMD: 3 rice and 2 rice (*i.e.* 3 or 2 rice crops per year respectively), Vegetables, Aquaculture (Shrimp), Fruit trees, Rice - shrimp.

The *farming unit* is the key entity of the model. It represents both the farmer (with its decision-making capabilities) and their agricultural parcel, which contains a land-use type. It is represented as a 500 m x 500 m cell (the resolution depends on the input data). It is located

[Figure 3.1]
Main entities of the LUCAS-GEMMES model



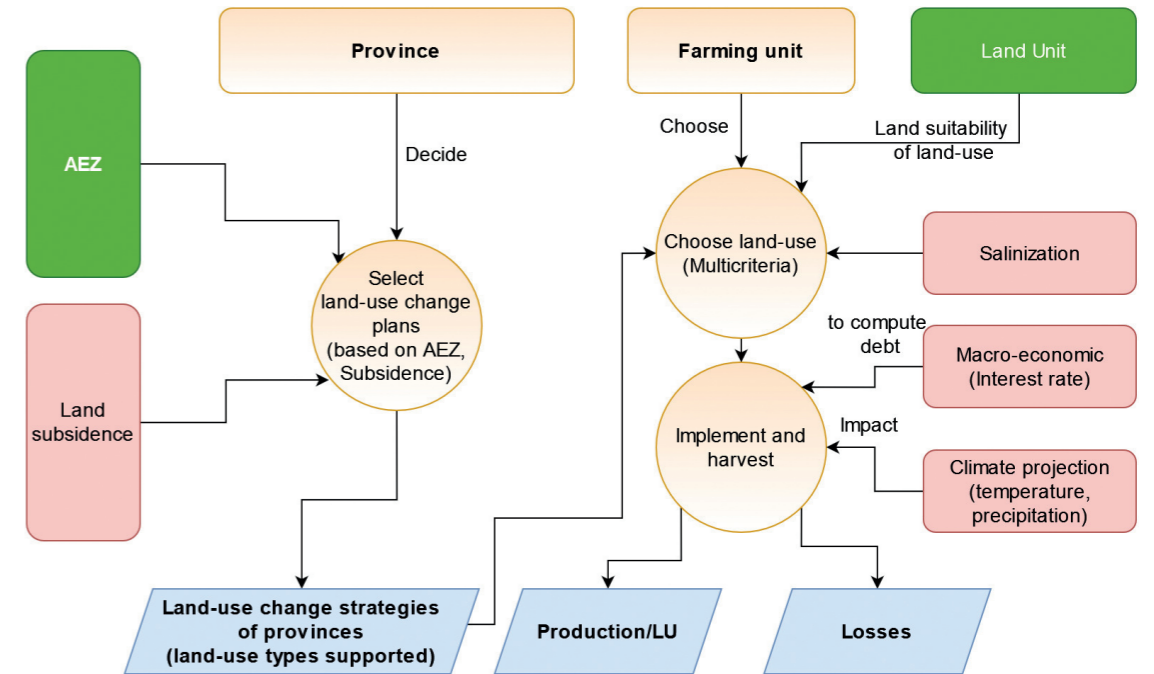
in a province and a land unit. It is also characterized by individual annual income linked to cultivation activities and losses due to impact of climate change.

A *Province* entity is characterized by its name, location and spatial extent, its total budget for loan to farmers each year. The province is located in one or several agro-ecological zones. Thus, it will be able to choose an adaptation strategy for each of its farming units depending on the AEZ and a land subsidence threshold. Each strategy is defined as a list of permitted and prohibited land uses for a threshold in each AEZ.

All these agents are embedded in a global environment defining global variables and in particular providing data coming from exogenous submodels such as interest rate (*macroeconomic* submodel), map of temperature and precipitation (*climate* submodel), map of cumulated land subsidence (*subsidence* submodel), and dry-season surface water salinity map (*salinity* submodel).

The spatial resolution for the farming unit is set to 500m x 500m. Each simulation step lasts one year. The simulation starts in 2015 and stops in 2050.

[Figure 3.2]
Conceptual model of LUCAS-GEMMES



Process overview

The main processes of the LUCAS-GEMMES model are detailed in Figure 3.2. During a simulation the global data from exogenous models are updated with a frequency depending on the submodel: subsidence maps are updated every 10 years, macroeconomic and climate data are updated yearly, and the salinity map is updated every 20 years. From these updated data, exposed areas (i.e. areas where climate and salinity conditions overtake the tolerance of rice and shrimp [Truong et al., 2021]) are computed. Concerning the impact of subsidence, we assume that, beyond some threshold, cumulated subsidence will impact agricultural production by decreasing the income of farmers.

Provinces choose adaptation strategies for land-use change: depending on the AEZ and the situation of the land subsidence, they choose to allow or prohibit the land-use switch toward some other specific land-uses. Each province can have one or many strategies for the AEZ and the situation of land subsidence (e.g. living with floods, living with floods but saving groundwater): for each AEZ, the province chooses the land-uses allowed depending on a land subsidence threshold reached in the area. This choice corresponds roughly to allowing the pumping of groundwater for agricultural activities, or not. As the subsidence maps are updated every 10 years, the strategies are reevaluated with the same frequency, which corresponds to the plan period in Vietnamese land-use planning.

Finally farming units select land-use candidates from the ones allowed by the strategy of the province (policy), then choose the land-use based on multicriteria decisions that match land unit, income, ability to change (technically), and impact of neighbors (land-use of neighbors) (detailed in Section 3.3 [Decision of Farming Unit with constraints of province strategies](#)). Farming units have a budget to switch or maintain the current land-use. They may need an additional budget in the event of a change in land-use; if so, they ask for a new loan (depending on the interest rate). At the end of each year, farming units update their budget and income. In the event that a farming unit was impacted by climate conditions, they will lose the income of the year and individual losses increase in line with cost of implementation. The province updates total household losses at the end of each year.

At the end of each year, the model provides a land-use map, total area for each land-use type, total income from agriculture activities, water demand, and losses caused by climate change and subsidence by province (for each of their AEZ), and for the whole VMD.

3.2 Implementation of the LUCAS-GEMMES model

Input data

Input data of the LUCAS-GEMMES model include the data from the LUCAS model presented in [Truong et al. \(2021\)](#): land-use map in 2015, land unit map, dry-season salinity maps¹ for 2030 and 2050 under RCP 8.5 scenario (taking into account global sea-level rise and fluvial discharge changes) [[Eslami et al.](#),

1. 90th percentile salinity value during the dry season.

2021], maximum and minimum of monthly temperature, and minimum of total precipitation per month in the dry season. The climate data (temperature and precipitation) is aggregated from 31 CMIP6 global climate models (scenario RCP 8.5) projections, downscaled for Viet Nam at 25 x 25 km spatial resolution.

Additional data include the provinces and agro-ecological zones, land subsidence map, and economic data (price and interest rates).

All the raster data (land-uses, subsidence, salinity map, etc.) were resampled with the nearest neighbor method for the same resolution, which is 500 m x 500 m for each pixel.

Provinces and AgroEcological Zones

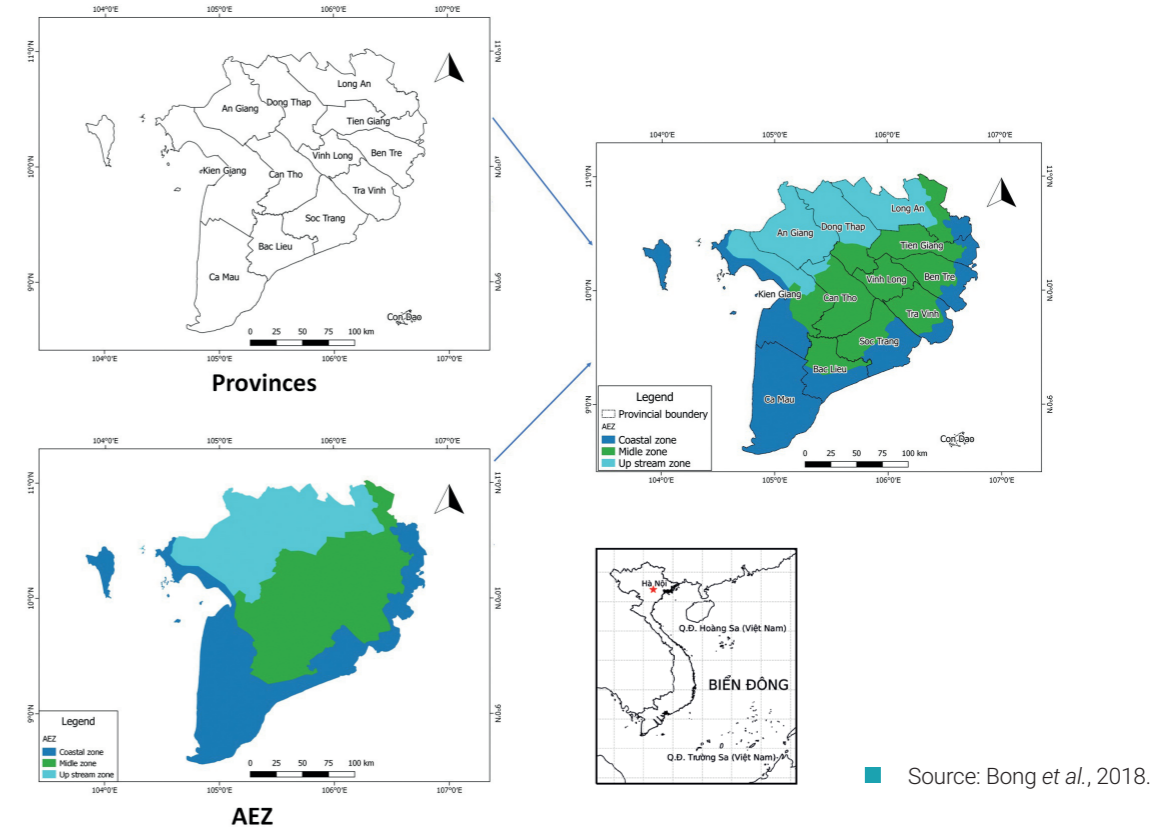
We use Province and AgroEcological Zone spatial data [[Bong et al., 2018](#)] to initialize the related entities. The province is the key administrative level in Viet Nam. Note that we focus on the Vietnamese Mekong Delta only (*i.e.* the continental part of the provinces). In particular, islands such as Phu Quoc, Con Dao, or Nam Du are not taken into account in the model, whereas they are part of the provinces under consideration. AgroEcological Zones are defined to be a homogeneous area in terms of ecological and agricultural features.

The two types of entities are spatially related: a province contains 1 to 3 parts of the different AEZs.

Land subsidence and water demand of land-use

[Minderhoud et al. \(2020\)](#) showed the importance of land subsidence for the future evolution of the Vietnamese Mekong Delta, and the fact that it can have stronger and faster effects than climate change-induced global sea level

[Figure 3.3]
Spatial relation of provinces with agro-ecology zone



rise, at least for the first half of the century. Another important conclusion of this work is that the main driver of current high subsidence rates recorded in the Delta is groundwater extraction.

In [[Minderhoud, et al., 2020](#)], the authors simulate land subsidence in the Mekong Delta with a time horizon of 2100, depending on several scenarios of groundwater extraction pathways: B2 corresponds to annual growth corresponding to 4% of 2018 volume, B1 to 2% of 2018 volume, M1 to 0% growth after 2020, M2 (resp. M3 and M4) to a gradual reduction of water extraction towards 50% (resp. 25% and 0%) of 2018 volume.

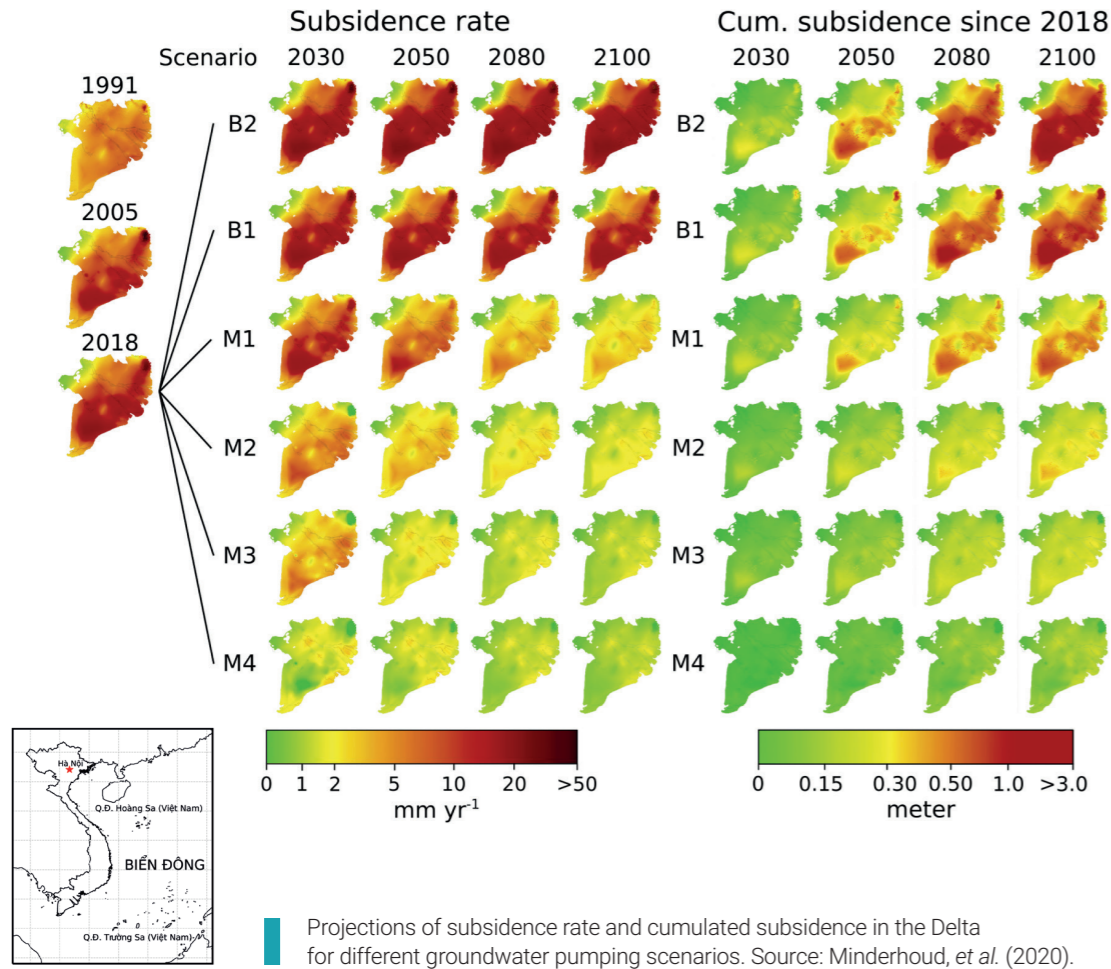
In the model, we focus on the two non-mitigation scenarios (B1 and B2) and the mitigation strategy M1 (maintenance of the same water extraction level). For each scenario, we use a raster data file for every 10 years (2020, 2030, 2040, 2050) containing the cumulated land subsidence of the whole Delta (see [Figure 3.4](#)). All the data have been provided by P. Minderhoud and correspond to that presented in [[Minderhoud, et al., 2020](#)].

Economic data

As presented in [[Truong et al., 2021](#)], the cost and benefit of each land-use (as summarized in [Table 3.2](#)) are used in a multi-criteria deci-

Source: Bong et al., 2018.

[Figure 3.4]
Projections of land subsidence



[Table 3.1]
Water demand of the various land-uses in the dry season

Land-use	Volume (m ³ /ha/season)	Reference
3-rice crops	7 500	Water needs for Winter-Spring according Viet Nam Standard TCVN 8641-2011 (Viet Nam Standard, 2011)
Vegetables	4 658	Vuong & Thach (2019) pointed that the water volume of Green asparagus was 4658 m ³ /ha/season
Fruit trees (Pomelo, mango, longan...)	13 200	100 liters/tree of 6 year old * 10 times/month * 6 months * 2000 trees/ha (ATESO, 2018)

[Table J5]
Average cost and benefit of dominant land-use types in the Vietnamese Mekong Delta

Land-use type	Income (Million VND/ha)	Cost (Million VND/ha)	Labor (Days/ha/year)
3-rice crops	58.48	52.31	92
2-rice crops	42.42	34	78
Rice - shrimp	86.62	61.38	86
Fruit trees	184.00	62	115
Vegetables	88.07	114.24	233
Aquaculture (Shrimp)	277.23	308.18	217

■ Source: Data survey in Soc Trang Province in 2018, Nguyen *et al.*, 2019; Nguyen, 2021.

sion-making process for farmers when they need to decide which land-use to implement in their farming unit. Income is a key factor in the farmers' decision [Nguyen H. T. *et al.*, 2019].

The cost for Farming Units of the land-use implementation is based on the cost of each land-use type, but also on the cost of credit that could be necessary. The latter is highly dependent on the interest rate. The model thus uses a projection of interest rate evolution developed in the frame of the GEMMES project [provided by Espagne *et al.*, 2021]. This variable enables losses to be calculated in the event that the area is impacted by climate change, saline water intrusions or land subsidence.

Simulation initialization

Initially all the spatially located agents are initialized using the dedicated data file. Then through spatial queries, provinces, AEZ, and Farming Units are linked together (*i.e.* which AEZ is contained in which province, which province or AEZ belongs to which Farming Unit,

which subsidence for which Farming Unit or province, etc.). A Farming Unit recognizes the Land Unit, subsidence regions, and the province that it is located in, in order to adapt to the natural conditions and province strategies.

Parameters

The LUCAS model came with a set of parameters (presented in Table 3.3) related to the farmer's decision-making process (the weights related to each criterion) and the tolerance of crops to temperature and precipitation. These parameters have been calibrated by Truong *et al.* (2021) on land-use data.

The LUCAS-GEMMES model introduces one additional parameter that will be explored by simulation in the following Section 4.3: the subsidence threshold used in the province and individual decision-making process.

The climate scenario and subsidence scenario could also have been parameters. To limit the computation time, we have chosen a single climate scenario and a single land subsidence scenario (the worst-case).

[Table 3.3]

List of parameters explored in the LUCAS model

Parameter	Explanation
W_{profit}	The weight profitability criteria
$W_{suitability}$	The weight of suitability criteria
$W_{LU_ability}$	The weight of agriculture technical convertibility criteria
$W_{influence_neighbors}$	The weight of influence index of neighbors
Tolerance temperature for rice	The maximum temperature tolerated
Tolerance precipitation for rice	The minimum precipitation tolerated
Tolerance temperature for shrimp	The maximum tolerable temperature for shrimp
Tolerance precipitation for shrimp	The maximum rainfall sensitivity by shrimp
Subsidence threshold	The subsidence level at which provinces and individual farmers decide to apply adaptation or mitigation strategies

Indicators

The LUCAS-GEMMES model aims to evaluate the effects of adaptation strategies (by farmers and/or guidance by provinces) on land-use distribution. To this end, it has proposed several indicators related to the distribution of each land-use in the Delta, the exposed and vulnerable areas, and the total amount of farmers' losses and benefits.

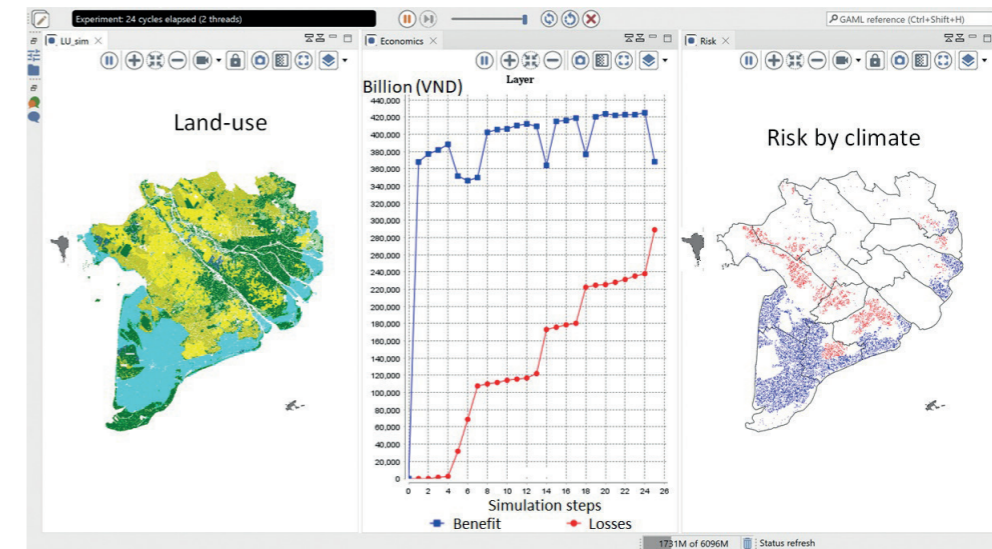
(i) Land-use maps and land-use areas

In order to observe the evolution of the spatial distribution of each land-use type, the first indicator provided with the LUCAS-GEMMES model is the map of land-use as a raster map: each pixel (corresponding to a Farming Unit) is displayed with a color representing its land-use type, selected from 3-rice crop, 2-rice crop, Annual crops, Fruit trees, Aquaculture, Forest and Rice-Shrimp (*i.e.* aquaculture). This map also displays the province boundaries to ease analysis at that scale. Figure 3.5 illustrates an example of the simulation's graphic user interface. The left part contains the land-use map.

From this spatial data, we provide an aggregated indicator that helps to quantify the evolution of each land-use area: the surface of each land-use type at the scale of the whole VMD. Even if it is not used here, more precise indicators could be computed if there is a need to analyze the evolution of land-use types at the scale of a province, district, etc.

(ii) Vulnerability maps

In order to identify the areas that may be particularly impacted by environmental changes, the LUCAS-GEMMES model computes whether a Farm Unit is exposed (*i.e.* environmental conditions may damage the crop). We here consider only the effects of changes in temperature, precipitation and salinity intrusions due to climate change. Two types of land-use are distinguished: rice culture (3-rice crops) and aquaculture (shrimp). Concerning rice culture, if the cell concerned is located in an area protected by dyke systems, but the monthly highest temperature in the dry season (December to May) exceeds the rice tolerance threshold and the rainfalls are lower than the tolerance rainfall threshold, the crop is considered risk-exposed.

[Figure 3.5]
LUCAS-GEMMES Graphical User Interface

An example of the LUCAS-GEMMES Graphical User Interface, displaying (left) the land-use map, (center) the evolution of benefits and losses, and (right) the vulnerability map (blue: exposed aquaculture cells; red: exposed rice crop cells).

Aquaculture cells are evaluated as risk-exposed when precipitation is above the cut-off threshold (reducing salinity in the ponds). From this information, a map of vulnerability can be plotted (such as the right part of Figure 3.5). To simplify the visualization, we display only exposed pixels with aquaculture (in blue) and rice crops (in red).

(iii) Water demand of land-use types

As highlighted in Minderhoud *et al.* (2020), groundwater pumping is a highly significant factor in predicting the evolution of land subsidence in the VMD. To estimate the evolution of groundwater pumping volumes under the influence of the adaptation strategies, we compute the evolution of the water demand index for agricultural purposes, depending on the land-use type. The water demand index is calculated to provide an overview of water

availability, based on estimated water volumes from usage patterns. This indicator enables the overall water demand of the options to be assessed, to assist in considering the water-saving aspect of the experiments. The calculation of this indicator is not intended as an accurate calculation of the amount of water used according to FAO Penman-Monteith [Allen *et al.*, 1998], nor of the impact of climate change on the water demand of crops. Therefore, this indicator in LUCAS-GEMMES is defined as the annual dry season water requirements of land-use patterns for the study area based on reference sources [Table 3.1].

(iv) Income from agricultural activities and losses triggered by climate change and subsidence

In order to assess the economic impact of land subsidence and the application of the

various adaptation strategies, two economic indicators have been implemented:

- the total **income** of the farmers computing from all the crops in the VMD. As detailed in Section 3.3 **Economic submodel: computation of income and loss**, incomes are computed on the basis of data provided in Table 3.2.

- the total **loss** of farmers due to environmental changes. For each crop, if it is in an exposed area, its production is destroyed, its income is reduced to 0, and the invested money is added to the total loss indicators.

These 2 indicators are aggregated at the scale of the whole Delta.

3.3 Sub-models

We describe in the following sections the various dynamics in detail.

Province decisions

The province adaptation strategies that have been implemented are based on the recommendation presented in Resolution 120/2017, and are chosen depending on the AEZ and land subsidence under consideration. Decision 324 also provided the main guidance for 3 AEZ.

A Province adaptation strategy consists in prohibiting the installation of new land-use for some given types: a strategy defines whether a farmer is allowed to switch its current land-use towards another one. This strategy aims only at preventing the implementation of new land-uses for some given types; the rules are thus independent of the current land-use. Table 3.4 summarizes all the possible strategies. As an example, if the province chooses the Living with flood strategy, it becomes for-

[Table 3.4]
List of the Province adaptation strategies based on AEZ and subsidence

Adaptation strategy	AEZ name	Subsidence level	Land-use change policy					
			3 rice	2 rice	Vegetables	Shrimp	Fruit trees	Rice - shrimp
Living with flood	Upstream zone	subsidence	A	A	A	N	N	N
Optimize farmer income	Middle zone	level < threshold _{AEZ}	A	A	A	N	A	N
Living with salt water	Coastal zone		N	A	A	A	A	A
Living with flood, protect groundwater	Upstream zone	subsidence level > threshold _{AEZ}	N	A	N	N	N	N
Optimize income, protect groundwater	Middle zone		N	A	N	N	N	N
Living with salt water, protect groundwater	Coastal zone		N	A	N	A	N	A

■ Notes: A = Allowed, N = Not allowed.

bidden to change any land-use to shrimp, rice-shrimp, and fruit trees.

A strategy is chosen depending on the AEZ but also the land subsidence level and a subsidence threshold: the province will choose to protect groundwater if the subsidence level is greater than its threshold for this AEZ (which is defined in the Experiments).

Decision of Farming Unit with constraints of province strategies

Select land-use

At each simulation step (*i.e.* each year), farmer agents are able to change their land-use type. To this end, each farmer agent first evaluates the benefits provided by the conversion to each existing land-use type allowed by the Province in its AEZ and land subsidence level, using a weighted mean of the four following criteria, and then selects the land-use type that maximizes it. In order to take the intrinsic inertia of these product change processes into account, we consider that only some of the farmers (randomly selected) will be able to change their land-use at each simulation step. This number of farmers will be defined from a conversion rate parameter.

Let *i* be a farming unit agent, *l* be the current land-use type on the associated farming unit, and *l'* the new land-use type to evaluate; the benefit to convert from type *l* to *l'* is calculated as follows:

- W_c the weight of the criteria *c*. Values have been obtained by calibration by using land-use map in 2015 [Truong *et al.*, 2021].

- $Val_c(i, l, l')$ the value of the criteria *c* for a conversion from the land-use type *l* to the land-use *l'* for the farmer agent *i*.

$$convertibility(i, l, l') = \frac{\sum_{c \in \{profit, suitability, ability, others\}} W_c \times Val_c(i, l, l')}{\sum_{c \in \{profit, suitability, ability, others\}} W_c}$$

Four criteria are taken into account:

- **Profit**: The yearly profitability of each land-use type is one of the main reasons leading to land-use conversion. This factor is an economic adaptation when people try to find a suitable farming model to improve their lives.

- **(Land) suitability**: This criterion represents the adaptation of a land-use type (*i.e.* an agricultural activity) to a specific environment. When environmental conditions change, the adaptation level of land-use types also changes. The suitability evaluation is performed according to the FAO's work [FAO, 1981]. The four suitability levels are standardized from 0: non-suitable to 1: most suitable.

- **Ability (to convert)**: This criterion measures how convenient it is to switch from the current land-use to another one. In farming systems, the transition from one type to another depends on the conditions in which new farming types can be established. In some cases, some switches (*e.g.* from shrimp to fruit trees) will be very difficult, whereas a switch from deep shrimp ponds in intensive shrimp farming to rice cultivation will not be possible. This ability criterion value is computed using a table of values associated with each transition LandUse1 → LandUse2.

- **(Influence of) others**: As shown by some studies, farmers are influenced in their production choices by their neighbors [Le *et al.*, 2008]. The value of this criterion corresponds to the proportion of farmer agents in the immediate neighborhood (the 8 cells around the cell representing the farmer) who have chosen this type of land-use.

Economic submodel: computation of income and loss.

As described more in detail in [Truong *et al.*, 2021], given the spatial distribution of land-use, environmental data (soil type, salinity,

etc.), and climate data, the model computes whether each Farming Unit is exposed to climate change-related risks. If such is the case, the Farming Unit will lose its investment (as its land unit crop will be destroyed). It thus does not receive any income from its crop and in contrast it increases its loss.

These income and investment costs are computed as follows:

$$\begin{aligned} \text{Investment} &= \text{cost}(\text{LandUse}) * \text{areaSize} * (1 + \text{interestRate}(\text{year}) / 100) \\ \text{Income} &= \text{income}(\text{LandUse}) * \text{areaSize} \end{aligned}$$

During the harvesting step, if the land unit is in the risk area, the income is reduced to 0 and the loss increases.

$$\begin{aligned} \text{Income} &= 0 \\ \text{Losses} &= \text{Losses} + \text{Investment} \end{aligned}$$

4. Experimental design

In order to test the impacts of the various adaptation strategies in terms of subsidence threshold and cooperation among provinces, we have conducted a set of experiments described in this Section, and whose results are analyzed in Section 5. We investigate two baseline situations and the combination of the various cooperation strategies and subsidence thresholds:

(i) Experiment 1: Baseline 1. An ideal baseline situation where subsidence does not have any effect on production and where no adaptation strategy is selected at the level of provinces and individuals [Section 4.1];

(ii) Experiment 2: Baseline 2. A baseline situation where subsidence impacts the benefit of land-use production, but where the adaptation strategies are chosen without taking subsidence into account, as proposed in Resolution 120/2017 [Section 4.2];

(iii) Experiment 3: individual adaptation. Subsidence impacts benefits and individuals choose their adaptation strategy depending on a subsidence threshold parameter;

(iv) Experiment 4: individual and provincial adaptations. Subsidence impacts benefits and both individuals and provinces choose their adaptation strategy depending on a subsidence threshold parameter.

In all these experiments, we have chosen the worst-case scenario for subsidence: the B2 scenario from [Minderhoud, *et al.*, 2020], corresponding to an annual growth in groundwater extraction of 4% of 2018 volume.

To assess and compare scenarios, key indicators will be the distribution of land-uses and the debt and benefits of the Farming Units.

4.1 Experiment 1: Baseline 1 - No provincial adaptation strategies and no subsidence impact

This first baseline experiment considers an ideal situation without any subsidence impact: the effects on subsidence are not taken into account in either land-use choice or land-use production. This situation is the one that has been explored in [Truong *et al.*, 2021] with the LUCAS model. Land-use choice is thus only impacted by climate change-related factors (temperature, precipitation, salinization due to climate change).

To implement this baseline 1 experiment, no parameters need to be explored, as they do not have any impact on the results: all land-use changes are allowed, except those constrained by changing climate conditions.

4.2 Experiment 2: Baseline 2 - No adaptation strategies while subsidence impacts the benefit of land-use production

In this second baseline experiment, we consider the situation where subsidence impacts land-use benefits, but where (individual or province) adaptation strategies do not take it into account. We assume that the benefit of land-use will decrease when subsidence occurs. This means that all land-use changes are allowed by the Province independently of the land subsidence level. In this baseline experiment, we want to show the land-use and other indicators when people do not recognise the impact of subsidence or when they do not know how to adapt specifically to subsidence. This is the baseline to which the following experiments will be compared.

4.3 Experiment 3: Individual adaptation strategies against the impact of subsidence

This third experiment corresponds to the exploration of individual adaptation strategies taking the subsidence level into account, based on Baseline 2: subsidence impacts the benefits of land-uses. In this experiment, provinces do not apply adaptation strategies depending on the subsidence level. This experiment thus explores the situation where farmers react without any guidance from local governments.

The farmers' selection is impacted by decreasing profits, and the profit impacts land-use selection. The subsidence adaptation strategy is triggered only when cumulated subsidence reaches a given threshold. That is the parameter that will be explored in this experiment: it may take a value among 0.1 m, 0.2 m, 0.5 m, and 1 m.

4.4 Experiment 4: Province and individual adaptation under impact of subsidence

The fourth experiment is based on Resolution 120/2017: it promotes new strategies in the VMD to deal with the effects of climate change. A specificity is that the Resolution introduces the notion of AgroEcological Zone, in which specific strategies should be applied. In the Upstream zone, a "Living with flood" strategy is recommended, in the Middle Zone an "Optimize farmer income" strategy, and in the Coastal Zone, a "Living with salt water" strategy. All these strategies are the ones presented in Table 3.4, applied when the land subsidence level is higher than the given subsidence threshold.

This fourth experiment is based on Experiment 3, to which an adaptation mechanism implemented at the province scale has been added. As a consequence, Experiment 4 considers the situation where subsidence impacts land-use benefits, and where both individuals and provinces apply subsidence-related adaptation strategies when the subsidence level reaches a given threshold. Individuals will thus choose their land-use under the possible constraints of the province, and the impact of the subsidence on their current land-use.

5. Results

The 4 experiments of the LUCAS-GEMMES model described above were launched on the GAMA platform [Taillandier *et al.*, 2019] in its 1.8.2 RC1 version [<https://gama-platform.org/>] at the scale of the whole VMD.

The results of the 4 experiments are analyzed through 5 indicators (see Section 3.2 **Indicators** for more details):

- (i) Map of land-uses in 2050 and area of dominant use types;
- (ii) Areas vulnerable to climate change and land subsidence;
- (iii) Water use savings in the dry season to fight land subsidence;
- (iv) Incomes from experiments with different response levels to the effects of subsidence;
- (v) Total economic losses in the agricultural sector due to environmental changes.

These indicators are presented and analyzed separately in the next sections. However, to have a clear overview of the situation, it is necessary to consider, analyze and synthesize all of them together.

5.1 Land-use maps and land-use area

Land-use maps are the leading criterion taken into account by environmental and agricultural policy makers for sectoral planning. **Figure 3.6** displays the land-use spatial distributions resulting from the 2 baseline experiments and the 2 experiments with applying adaptation strategies: the subsidence threshold to trigger adaptation strategies is chosen at 0.1 m for these 2 experiments. For the sake of space, we have limited our results to a single subsidence threshold, the one that provides the

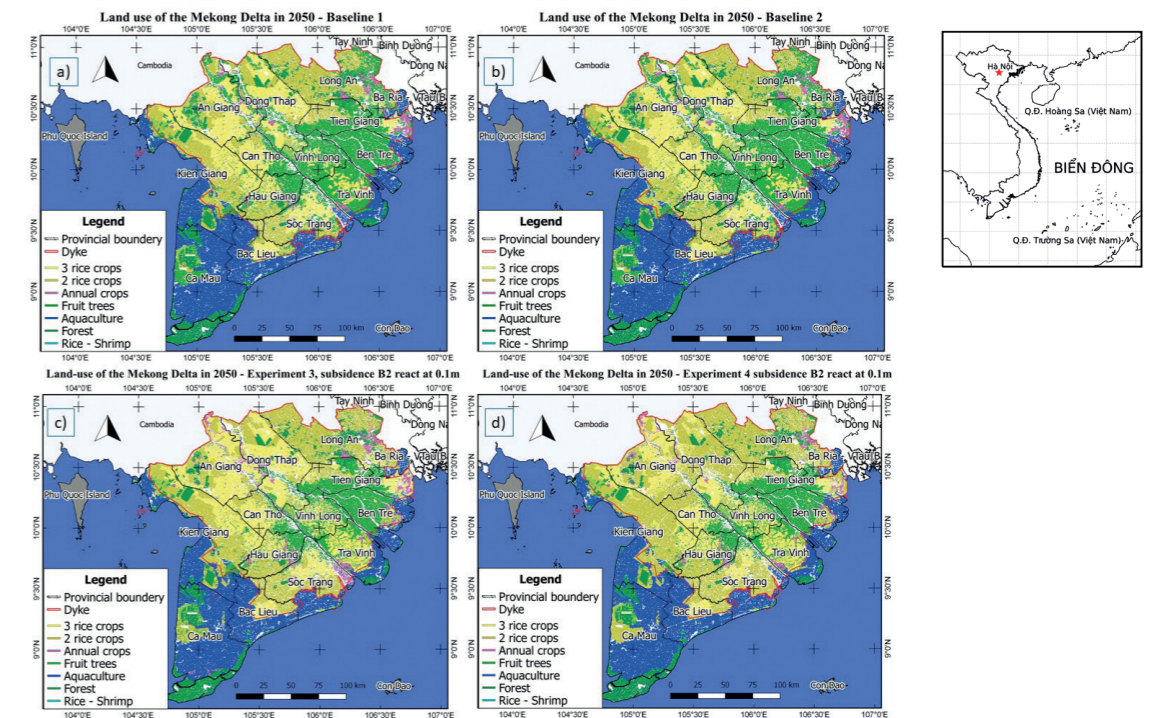
most different results. To analyze the results, we will cluster land-uses in 2 main groups: tree-crops (fruit trees, 2 and 3-rice crops, etc.) and aquatic land-use (rice-shrimp, shrimp, etc.).

As depicted in **Figure 3.6 (a)** and **(b)**, the land-use maps from Experiment 1 and Experiment 2 are similar: the aquaculture area has expanded between now and 2050, 3-rice crop land-use still dominates in the Upstream zone, and fruit trees occupy the Middle and Coastal zones. This is a normal trend as people have shown a tendency to choose land-use mainly based on the existing tradition of production, profit and no pressure in conversion without taking into account the risk factors due to climate and the impact of land subsidence, lack of surface water and groundwater in extreme conditions.

For Experiment 3 [**Figure 3.6 (c)**], as individual farmers take the impact of subsidence on incomes into account, attempting to reduce their water demand in the dry season in the Coastal area, the level of conversion to fruit trees in Ben Tre and Tra Vinh appears lower than in the two baseline experiments. Similarly, 3-rice crops land-use in Soc Trang and Bac Lieu has almost disappeared, mostly replaced by 2-rice crops.

Considering Experiment 4 [**Figure 3.6 (d)**], where the adaptation policy of the provinces is applied based on the characteristics of the AEZ and the land subsidence, the spatial land-use distribution map is largely different in terms of rice crop land-uses. Land with 2-rice crops prevails in the whole Delta, whereas different adaptation policies are applied. For the An Giang and Dong Thap Muoi provinces, the policy of flood discharge and crop cutting following the spirit of Resolution 120 has oriented the deve-

[Figure 3.6]
Land-use map in 2050 of 4 experiments



a) Experiment 1: Baseline 1; b) Experiment 2: Baseline 2, subsidence impact; c) Experiment 3 subsidence react at 0.1m; d) Experiment 4 subsidence react at 0.1m.

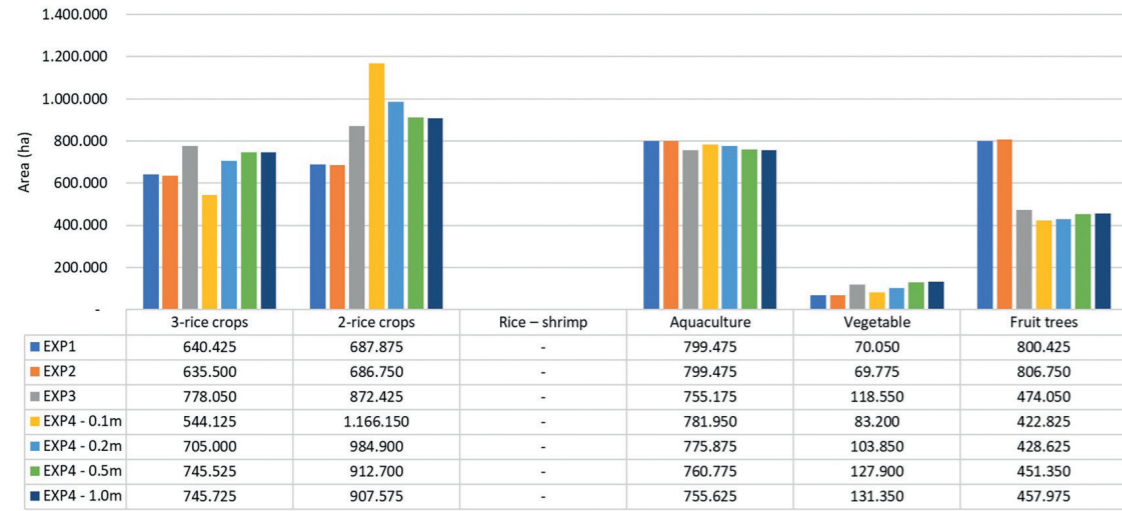
lopment toward 2-rice crops. We get a similar evolution for Soc Trang and Ca Mau provinces, with 2-rice crops in areas affected by saline intrusion. In parallel with the flood discharge policy, fruit trees only focus on developing in stable dike areas and the foothills, helping to avoid conflicts over surface water use.

In addition to the spatial distribution map (displayed in **Figure 3.6**), the total area of each land-use type is also important to support land management. **Figure 3.7** shows the total area for each land-use type over the 4 experiments. For Experiment 4, we display the results with the four values of the land subsi-

dence threshold (0.1, 0.2, 0.5 and 1.0 m) used to trigger adaptation strategies.

The results show a trend to transform 3-rice crops into other land-use types. While in Experiments 1 and 2, the 3-rice crops is strongly converted into fruit trees (in coastal provinces), in Experiments 3 and 4, a shift toward 2-rice crops appears clearly (in particular for low values of land subsidence threshold, *i.e.* in cases where either individuals or provinces apply adaptation strategies at an early stage of land subsidence). This is appropriate in case of extreme weather and policies to limit groundwater extraction. A second (smaller)

[Figure 3.7]
Area of land-use of 4 experiments in 2050

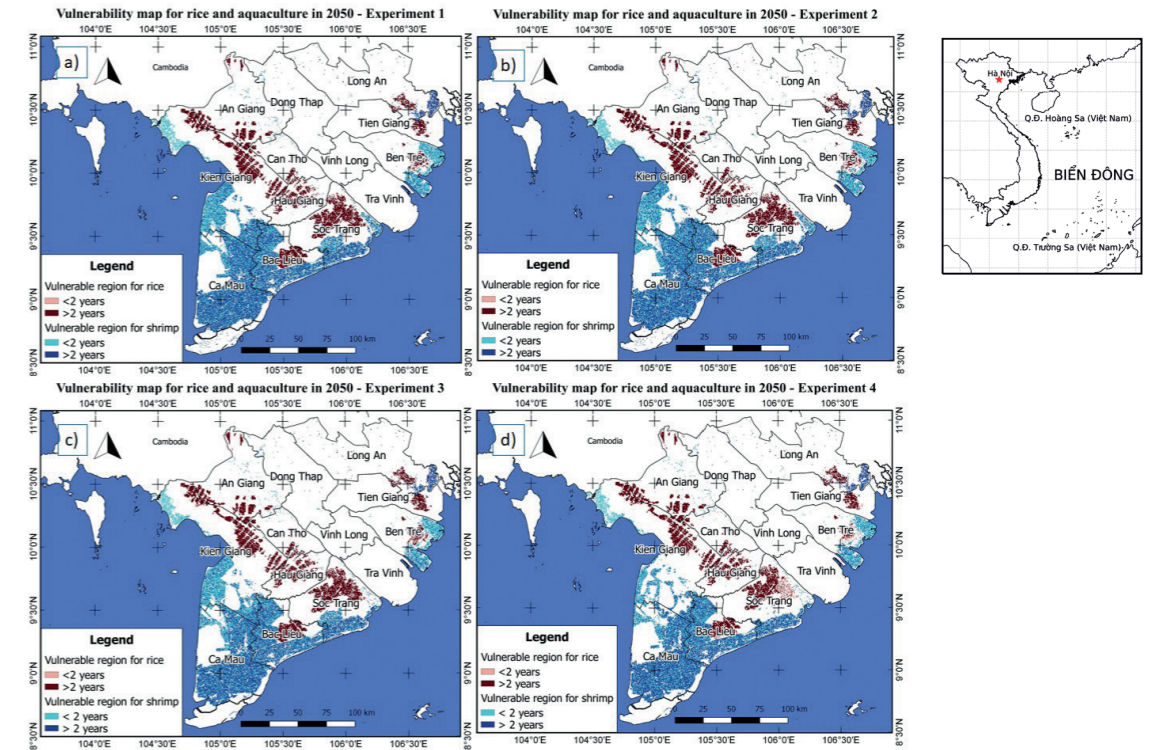


impact of the application of province adaptation policies (when the subsidence threshold parameter takes low values) is a reduction of the area for fruit trees and vegetables, and an increase in the aquaculture area. A special point that needs to be considered is that the rice-shrimp area in 2050 disappears. Based on the simulation results, all rice-shrimp areas were reduced gradually and converted to shrimp through to 2040.

The main result of the chart in Figure 3.7 presents different ways of converting 3-rice crops. In the baseline experiment, the 3-rice crops would mainly be converted to fruit trees in the coastal provinces (Ben Tre, Tra Vinh), while in experiments 3 and 4 they are converted to 2-rice crops. The total area of fruit trees in 2050 of Experiment 1 and 2 would be 800 to 806 million hectares: between 70% and 90% higher than in the adapted ones. This highlights the value of adaptation strate-

gies that protect groundwater and reduce the risk of water shortage for fruit trees in the dry season compared to the baselines. Inversely, when applying the policy to protect groundwater as soon as projected land subsidence reaches 0.1 m (EXP4 - 0.1 m): the area of 3-rice crops would be significantly reduced by conversion to 2-rice crops compared with the other adaptation experiments. The 2-rice crops area the event of provinces applying the adaptation for a subsidence threshold 0.1 m would be nearly 70% higher than the baselines (reaching 1.67 million hectares). However, there is not much difference when applying these strategies for the subsidence levels 0.5 m and 1.0 m. In terms of resource protection, applying early adaptation policies is crucial to resource protection. But the economic point of view needs to be considered and analyzed in Section 5.4.

[Figure 3.8]
Vulnerability maps of 4 experiments



a) Experiment 1: Baseline 1; b) Experiment 2: Baseline 2, subsidence impact; c) Experiment 3: subsidence react at 0.1m; d) Experiment 4 subsidence react at 0.1 m.

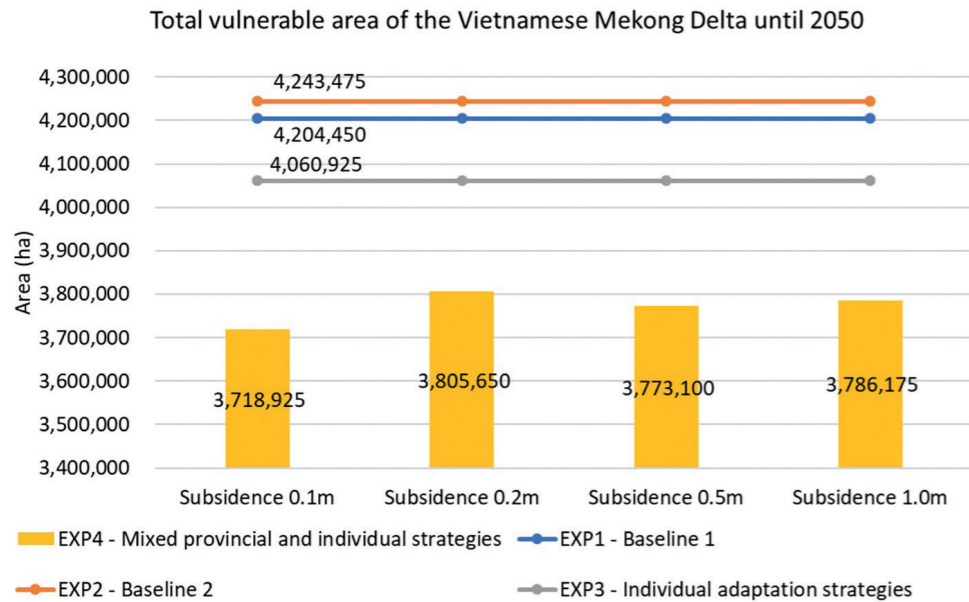
5.2 Vulnerability assessment

Figure 3.8 presents the vulnerability maps of rice and shrimp land-uses resulting from the four experiments (once again for Experiments 3 and 4, we only display the results for a subsidence threshold of 0.1 m). The LUCAS-GEMMES model computes these maps based on the number of years a land unit is at risk over the simulations. The more heavily impacted the area, the darker the color. In the two baseline experiments, these maps are similar. In experiments 3 and 4, some areas such as Soc Trang have reduced the vulnerable areas,

in particular for rice crops in the Coastal area (red color in the Figure 3.8), thanks to the application of adaptation strategies.

The maps for Baseline Experiments 1 and 2 show that the impacted areas are mainly located in Ca Mau, Bac Lieu (for shrimp), Soc Trang, Kien Giang (rice and shrimp), coastal regions of Ben Tre and parts of Tien Giang, An Giang, and Long An (rice). The provinces of An Giang, Dong Thap, Long An, and Tra Vinh contain large 3-rice crops areas but are not affected by climate conditions, thus the transformation from 3-rice crops to 2-rice crops

[Figure 3.9]
Vulnerable area for rice and shrimp of 4 experiments



in these provinces does not contribute to narrowing the vulnerable area in these provinces.

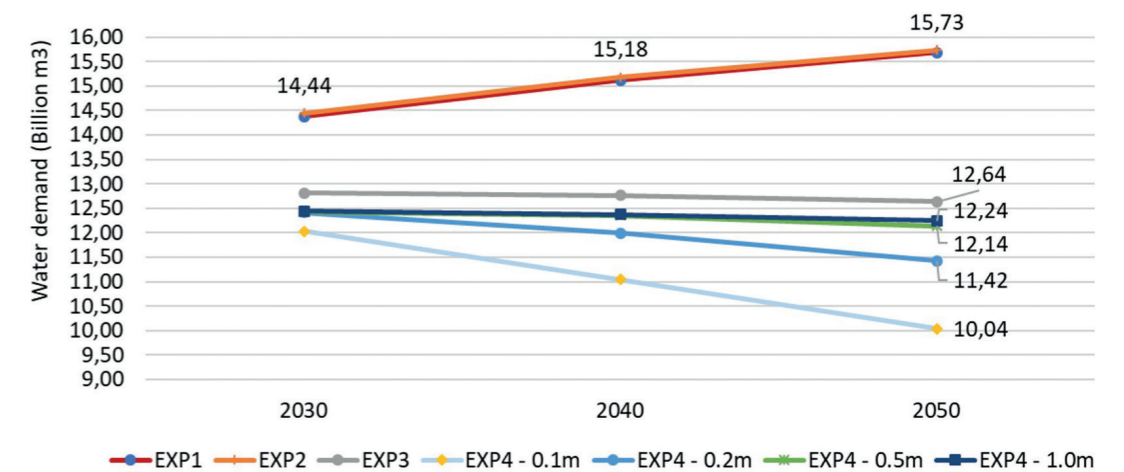
In order to compare the vulnerable area of the four experiments, we compute the total vulnerable area for rice and shrimp during simulation and plot it in Figure 3.9. First, it appears that the areas for Baseline 1 and Baseline 2 are significantly greater than for the two other experiments with adaptation. In Experiment 3, although the vulnerable area is significantly narrowed compared to the two baselines, the total vulnerability area when people self-adapt to subsidence levels was significantly higher (more than 300,000 ha cumulatively) than this area of Experiment 4 (provinces reacted at subsidence threshold from 0.1 m to 1.0 m). This is due to the fact that the multi-criteria optimal selection mechanism of farmers is still driven by the highest income (land-uses with the hi-

ghest profit are still occupying the area) and newly converted land-use was not supported for reducing risk. For Experiment 4, we can observe that the total vulnerable area is reduced even further; more specifically, when the province applies adaptation strategies early (i.e. with a low subsidence threshold), the affected area would be reduced by 50,000–80,000 ha compared to the cases of slow responses (subsidence thresholds higher than 0.2 m).

5.3 Water saving to mitigate subsidence

Evolutions in water volume demand, aggregated at the scale of the studied area, are plotted in Figure 3.10 for years 2030, 2040, and 2050. The two baseline Experiments 1 and 2 keep a high annual water use regime because farmers converted to land-use that

[Figure 3.10]
Water demand evolution



For the 4 experiments with various values of the subsidence threshold.

consumes much more water. For the experiments that apply provincial adaptation strategies, the results show that the amount of water used is reduced significantly compared to other cases when provincial strategies are early responses (saved more than 5 billion m³ in EXP 4-0.1m compared with the baselines). In the case of people’s self-awareness and early adaptation (EXP3-0.1m), the results show that the amount of water used is also significantly lower, even if this is not as efficient as the application of provincial adaptation strategies.

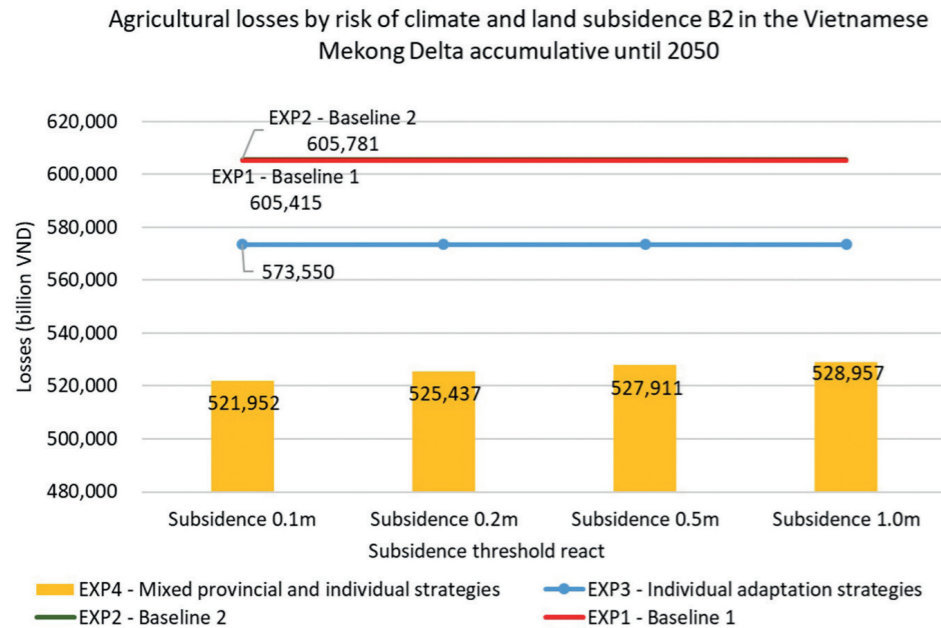
Considering the relationship between water demand and land-use [Figures 3.6 and 3.7], water demand reduction seems to be mainly due to the conversion from 3-rice crops to 2-rice crops. It is well noted that it does not directly help in reducing subsidence (because these cultivation types use surface water), but indirectly enhances surface water resources. In An Giang and Dong Thap areas, when cut-

ting crops and receiving floods, it serves to store surface water for cultivation. Besides, the saved water can be run off into canals and ponds to irrigate fruit trees and vegetables, where farmers can cultivate dry crops in the dry season.

5.4 Analyzing incomes and losses with adaptation strategies

Figure 3.11 plots the cumulative loss due to climate and salinity conditions in 2050. It shows first that Baselines 1 and 2 represent a significantly larger amount of financial loss than the two other experiments; this is coherent with the larger exposed area (as depicted in Figure 3.9). The results of Baseline 1 and Baseline 2 experiments are very similar and high, due to risk in aquaculture: the affected areas are mainly Farming Units with 3 rice crops and shrimp farming land-uses. We can

[Figure 3.11]
Accumulated losses of 4 experiments



nevertheless note that the loss values do not differ between Baseline 2 and Baseline 1, because they share the same land-use selection behavior.

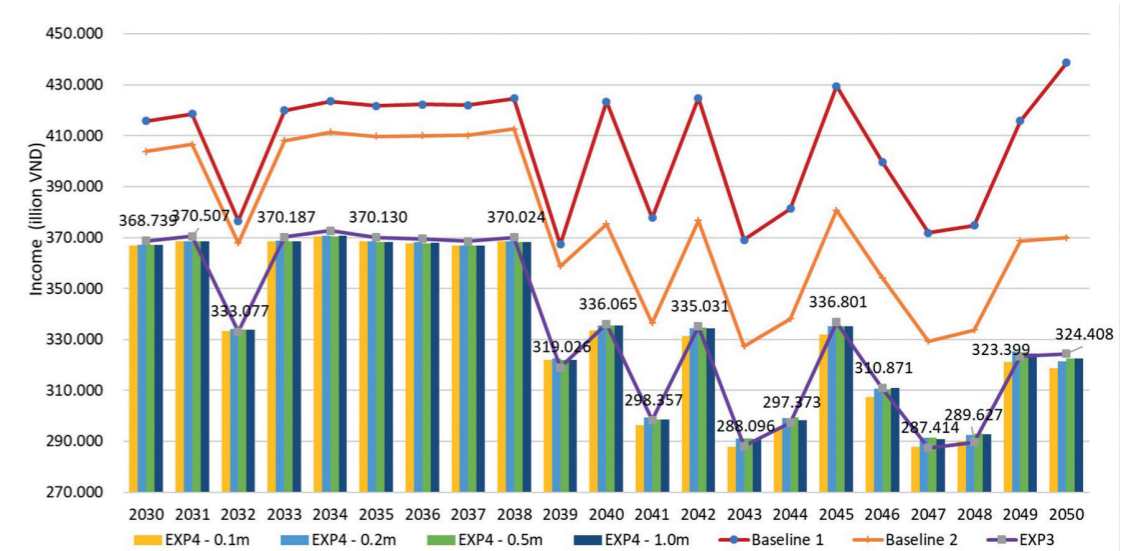
As far as Experiment 3 is concerned, the amount of money lost is lower than Baseline losses. This phenomenon occurs because farmers applied the adaptation strategies (selecting land-use based multicriteria evaluation among the land-use candidates, supported by the strategies of the province) so that vulnerability to climate, salinity and subsidence is reduced.

In Experiment 4, the loss is significantly lower than in Experiment 3, with a lower value showing an improvement in the situation when provinces apply adaptation strategies at a low subsidence threshold (0.1 m) compared to a late, serious threshold (1 m). Even if

the total losses of EXP4-0.1m are the lowest, large shrimp areas with investment levels around 6 times higher than for rice can be subject to potential risk from climate factors. From a qualitative point of view, the Province adaptation strategies (prohibiting some land-use from being created) seem to have a positive effect from an economic point of view, as they reduce losses; but when people select a new land-use, it can be impacted by climate change. This shows the need to invest in climate change-adaptive shrimp farming techniques to minimize the damage caused by climate change.

Figure 3.12 summarizes the results in terms of farmers' incomes. It compares the total incomes in the ideal case, when incomes are not affected by the subsidence (Baseline 1), with the situations where they are and no adaptation strategies are implemented (Ba-

[Figure 3.12]
Evolution of annual incomes for the 4 experiments until 2050



seline 2), and situations where adaptation strategies are applied (Experiments 3 and 4). The results show a large inter-annual variability of income, caused by strong impacts of weather conditions for some years (as simulated in the climate projections data used in this study).

Under ideal conditions, the transition to suitable farming systems with high returns would make a positive contribution to the economy of the Delta, despite the risks of climate change. However, when the impact occurs, profits drop significantly (Baseline 2). For the adaptation experiments, the experiments applying strategies at low subsidence levels showed a severe decline in incomes. In this situation, the conversion from 3 crops to 2 crops would strongly impact the income of farmers. The price to pay for protecting natural resources would be high in this case. However, when considering the impact of cli-

mate change and calculating the balance with costs lost due to impacts, it shows that choosing to apply a flexible adaptation strategy will bring great benefits to the people and better resource protection. Besides, farmers can choose highland crops in the dry season to improve their income.

6. Conclusion

This chapter aims to go one step further than [Truong *et al.*, 2021] in illustrating the possibilities offered by the agent-based approach to modeling socio-environmental systems. In particular, it introduces agents at a new decision-making level, the provinces, with the ability to influence or constrain, through regulations or incentives, individual farmers' decisions. These new agents also have new

perceptions and knowledge, such as land subsidence measurements, and an ability to use this information to make decisions that may differ from their neighbors, for example by applying different subsidence thresholds to trigger certain policies. This addition increases the richness of the behavior produced during the simulations, but in return, the model obviously becomes more complex to explore and interpret.

This chapter also illustrates the role that integrated models like LUCAS-GEMMES can play in combining the results of several other models at different scales. This is the case of those produced within the GEMMES project: downscaled climate projections from CMIP6 global climate models, inputs from the macroeconomic model [Espagne *et al.*, 2021] and projections from a land subsidence model [Minderhoud *et al.*, 2020] are all used to parameterize the scenarios used as contexts for the simulations. Finally, the chapter also provides an understanding of how certain policies described in legal decisions or reports can be implemented as behaviors or decision-making by artificial agents. This is the case, for example, with Resolution 120/2017 or Prime Minister's Decision 324/QD-TTg, both of which frame climate change adaptation policies in the Vietnamese Mekong Delta as well as the response to subsidence.

By adding the local adaptation behaviors of farmers, which were already presented in the first version of the model, LUCAS-GEMMES thus enables a wide range of adaptation and mitigation strategies to be explored. In particular, this can allow decision makers to analyze the results both qualitatively, in the form of combinations of local and global land use strategies, and quantitatively, in the form of indicators: farmers' income and losses, area

at risk of salinization due to climate change, estimated water used by crops, etc.

We found that the application of policies to restrict certain land-uses at low subsidence levels (0.1 m) is more effective in mitigating climate change risks. This is because it helps to reduce water consumption during the dry season and minimizes the damage caused by climate change. However, it has the negative consequence – when applied abruptly – of contributing to a decrease in farmers' income, which would tend to show the need, in reality, of additionally focusing on the construction of water supply structures, support for agricultural techniques or the development of dry season crops to improve people's livelihoods when an adaptation solution is chosen.

This lack of policy support for farmers from the provinces is one of the limitations of the current model. Another limitation is that LUCAS-GEMMES only takes the results of other models as input, without for the moment relying on a more important coupling: the choice of agricultural production thus has no influence on land subsidence, salinity intrusion or macroeconomic dynamics, which are considered as exogenous. This essential point, which greatly complicates the model but which appears necessary to increase its realism, will be further investigated in subsequent studies.

Despite this limitation, simulations using the current model were able to provide some interesting insights, particularly regarding the impact of cooperation between provinces, represented here as a coordinated choice of provinces sharing the same agro-ecological zone. These virtual experiments allow us to confirm numerically that coordination between provinces makes it possible to main-

tain farmers' overall incomes at reasonable levels, whereas the absence of coordination will penalize them. One of the interesting aspects of agent-based modeling is that it can explore not only the decisions, but also the interactions between actors at different levels. From this perspective, LUCAS-GEMMES could be a promising tool for policy evaluation

in the Vietnamese Mekong Delta, enabling awareness of the value of cooperation to be raised among provinces and national decision-makers, when a common property such as aquifer zones [Olstrom, 1990] is shared and exploited by several actors with sometimes divergent views

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