The impact of salinity intrusion on rice productivity

Soc Trang, Mekong Delta

A.M.(Lexy) Ratering Arntz

Thesis Report

ISBN 978-94-6366-008-2

TU Delft

The impact of salinity intrusion on rice productivity

Soc Trang, Mekong Delta

by

A.M.(Lexy) Ratering Arntz

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday January 15, 2018 at 12:00 PM.

Student number:	4177452	
Project duration:	February 2, 2017 – January 15, 2018	
Thesis committee:	Prof. dr. ir. S. Steele-Dunne,	TU Delft, Water Resources Management, Supervisor
	Prof. dr. ir. N.C. van de Giesen,	TU Delft, Water Resources Management
	Dr. ir. M. Rutten,	TU Delft, Water Resources Management
	ir. R. Molijn,	TU Delft, Remote Sensing
	ir. N. Wielaard,	Satelligence

TU Delft

Preface

This master thesis completes my engineering degree at the faculty of Civil Engineering and Geosciences of TU Delft. The past three years I specialized in water resources management; a field I feel very passionate about. The opportunity to work on this thesis project allowed me to combine my interests with new areas of study; remote sensing as well as agriculture. Seventy percent of all freshwater resources are used for agriculture to produce enough food for a growing population. With water resources increasingly under pressure due to climate changes and human extractions, the world's future food security is in jeopardy [30]. Through this project, I learned about the production of the third most cultivated (staple) crop worldwide, which is in many ways essential for food security and stability, especially in Asia. Furthermore, I became familiar with the world of remote sensing, including its exciting applications for agriculture and rapid scientific advancements.

I would like to thank Niels Wielaard from Satelligence for approaching Susan Steele-Dunne at the TU Delft with an exciting assignment to research the effect of salinity on agricultural activities using remote sensing in the Vietnamese Mekong Delta. The project combined several elements which I was looking for in a thesis; fieldwork abroad, interviews with farmers, remote sensing analysis, working in a project team (SAT4Rice [62]), agriculture and irrigation management. The remote sensing study pushed me to teach myself practical skills in GIS and python programming and to (hopefully) add scientific value. Through the social research part, I explored how mixed method research can be applied in practice. As always, encountering difficulties in both parts have taught me the most valuable lessons during my study.

To experience the Mekong Delta is a dream of every water resources specialist. Conducting research in one of the biggest delta river systems in the world is an incredible opportunity to learn about hydrological processes and tidal dynamics. Moreover, the delta has developed impressive intensive agriculture due to its fertile land and (overall) excellent growing conditions. The Mekong Delta looks like a tropical version of the Dutch polder landscape, which is easily traveled by bike. Needless to say that I quickly felt at home. They also say that people from the Mekong Delta are the kindest of the country, which I can attest to.

I would like to thank my friends at Can Tho University (CTU), Mi, Need and Du for their hospitality and kindness. Working together in a fieldwork team was the most fun experience of my thesis. For sharing their expertise and supporting my research at the university, I am grateful to Dr. Minh, Dr. Tuan and Mr. Quang from the land resources department, Dr. Tri from the Water resources department and Mr. Thai from the aquaculture department from the College of Natural Resources and Environment. Master and Ph.D. students including Trien, An, Hiep, Phuong, Mi and Need have been so helpful to give me comments, especially to improve the farmer surveys and Q-sort interviews.

Key advice at the right time during my period abroad came from Roman Sorgenfrei, a local development officer of GIZ working in Soc Trang. Thank you also for introducing me to the staff of the DARD of Soc Trang, including Ms. Ly, Ms. Thao, and Ms. Binh, who readily assisted my fieldwork in the province. Special thanks to Mr. Thu for accompanying me each fieldwork trip and making sure all paperwork and appointments were arranged in advance. Nanne Tolsma from Satelligence; thanks for checking in with me during my stay and introducing me to the Sat4Rice activities, including setting up a meeting Mr. A and Ms.Trang from Loc Troi Group. To Jessica; having a fellow European at CTU to explore Vietnamese culture in all its ways, definitely made my stay.

I am grateful for the remote sensing experts that I have been able to work with. They have shared with me their knowledge and responded ever cheerfully to all of my questions, however trivial they may have been at the start. Nguyen Ba Duy from the Remote Sensing Group of the Department of Geodesy and Geoinformation at TU Vienna corresponded extensively through email and Skype about his work on rice mapping with radar imagery. Vincent Schut and Rob Verhoeven at Satelligence processed data and assisted me with every programming and substantive issue that came up.

The best decision for my thesis was to work with Susan Steele-Dunne as my supervisor. I have been exceptionally supported and guided through the phases of scientific research as well as challenged content-wise. You have also just really inspired me by being a kick-ass female professor in science. Thanks to the rest of the committee members, Ramses Molijn, Martine Rutten and Nick van de Giesen for sharing their input and giving me some of their time to help me become a better researcher. I'm happy to have received permission to write part of my thesis as an article for publication which has thought me practical writing skills.

Most of all, I would like to thank my parents who raised me with the freedom to explore and pursue anything that inspired me. They have supported me through difficult times and helped me become a strong, flexible and open person. Without them, I could have never obtained the title of engineer. My sister and friends, for supporting and positively distracting me, as well as my dog; thank you all.

I look forward to apply what I have learned at TU Delft in my career as water resources and climate consultant. The interesting coursework, projects abroad, activities with the Watermanagement Dispuut and friends at the department have brought me so much in my student life. The financial support of TU Delft, the Dutch government and my parents enabled me to explore new places to find out how people cope with water issues all around the world. These experiences prepared me well for an international career in water engineering.

A.M.(Lexy) Ratering Arntz
Delft, January 2018

Abstract

More than half of Vietnam's national rice production is produced in the Mekong Delta. Many hectares of rice were damaged due to extensive salinity intrusion during the dry season of 2016. The impact of salinity intrusion on rice production is studied by (1) mapping the impact using remote sensing data (MODIS NDVI time-series) and (2) investigating how the impact affects farmers' lives. Ground data is collected in Soc Trang province through interviews with commune officials and farmers. Quantitative data includes damages to rice areas as aggregated by the local government and land use points for classification.

Rice areas are mapped through supervised classification, using extreme gradient boosting. Peak detection analysis is used to distinguish distinct rice cropping schedules within district boundaries. Compared against an evaluated climatology, hampered rice growth is mapped for two hot-spots (Long Phu and Nga Nam district). This can be attributed to salinity problems through interpretation of ground collected information and an understanding of the local salt-intrusion mechanisms. Reconciling affected rice grid cells mapped through satellite analysis with hectares of damaged rice recorded by the local government is difficult.

Analyzed perspectives of salinity affected farmers highlight the uncertain current conditions and future for rice production in the Mekong Delta. Local government officials and farmers feel the changing climate conditions and the urge to respond through preventive or adaptive measures to avoid similar impacts of salinity intrusion in the future. In this research, soft information gathered through interviews provided contextual learning opportunities to better direct, develop and interpret remote sensing analysis and results.

Contents

1 Introduction

Rice farming in the Mekong Delta (MKD) is a way of life. Around 12.5 million rice farmers in *the rice bowl of Vietnam* together supply 50% of country's national rice production on 12% of the land [55][91][50]. As a staple crop and main source of income for many farming households, rice production is important for local, national and global food security [47]. In the coastal provinces of the MKD, rice production was affected by salinity intrusion in the dry season of 2016. Rice fields were damaged because of a lack of available freshwater for irrigation. Consequently, farmer's rice yields significantly lowered. In some cases, saline water destroyed rice crops completely which pushed many farmers into debt.

According to the Ministry of Agriculture and Rural Development (MARD), rice production in the MKD was impacted at large scale by salinity problems. The company *Satelligence* posed the question whether this large negative impact can be mapped using remote sensing. No ground information on rice production and affected yields in the MKD was available to interpret remote sensing analysis; this information was to be collected. Conducting surveys and interviews with farmers and local government officials could be used to gather data, to develop a problem context as well as to understand local salinity intrusion mechanisms. Gathering perspectives of farmers and government officials on the salinity problems in the region could also be used to explore how remote sensing analysis could add value for farmers, rice companies, and agricultural planners in the MKD; possibly improving livelihoods for those who have been impacted most.

Therefore, a study on the impact of salinity intrusion on rice productivity in the affected coastal province of Soc Trang was organized with the support of Satelligence, TU Delft, Can Tho University and the Department of Agriculture and Rural Development (DARD) in Soc Trang.

1.1. Aims of this research

The aim of this research is twofold;

(1) to map the impact of the recent salinity intrusion event on rice productivity using remote sensing

In Vietnam, the rice farmer reports damages and (lowered) yields to the commune, the local government body, which aggregates yields and damages of rice cultivated areas and transfers this information to higher administrative levels. There is no spatial processing or analysis involved in recording this data, which could serve to gain insight into vulnerable rice areas. Satellite data can be used to monitor rice production and investigate spatial trends over time to support land use planning [43]. In turn, the intensely documented agricultural context of Vietnam could be used to validate remote sensing products and analysis. Remote sensing analysis and ground data collection combined can potentially contribute to mapping the severity and extent of the recent salinity problems.

(2) to investigate the impact of the recent salinity event on farmers' lives.

The damages to rice crops caused by the recent extreme drought and salinity event affected millions of farmers' lives in the MKD. The social research will give insight into the way farmers and governments cope with the salinity intrusion and how they perceive the problem. Furthermore, the recent salinity intrusion might have influenced perspectives on the future of rice production in the region. Current perspectives from farmers and local government officials on the future of agricultural management and various mitigation strategies are gathered.

1.2. Thesis outline

This thesis is presented in two parts. Part I addresses aim **(1)**, the value of remote sensing in mapping the impact of salinity intrusion on rice productivity. It is presented in the form of an article which will be submitted for publication in a peer-reviewed journal. Following the journal's prescribed layout, chapters include an introduction, materials & methods, results & discussion and conclusion section. Part I includes an extensive problem analysis (Chapter 2) and research site description (section 3.1), which is omitted in Part II.

Part II discloses the findings from the social research **(2)** and includes a short description of agriculture management and stakeholder analysis (Chapter 6) as well as a methodology (Chapter 7), results (Chapter 8) and discussion (Chapter 8) section. Finally, a synthesis chapter (10) will consider the overall conclusions of both research parts and their relation to one another.

I

Remote Sensing Article

2 Introduction

Rice is the third most cultivated crop worldwide in terms of production quantity [29] and feeds half of the world's population. More than 3.5 billion people depend on rice for more than 20% of their daily calories [34]. Asia accounts for more than 90% of the world's rice production, and Vietnam is the fifth largest rice producer with more than 44 million tons of rice harvested from nearly 8 million hectares of paddy field in 2014 [29] [46]. About one-fifth of the production quantity is exported for nearly 4 billion dollars, making Vietnam the second largest rice exporter in the world [29]. More than half of the nation's total rice is produced in the MKD, an important agricultural and economic region, often nicknamed *The Rice Bowl of Vietnam.* On the 65,520 km^2 low lying fertile plains of the MKD, 12.5 million people make a living from agriculture [55]. In addition to rice, 60% of the country's combined fisheries and aquaculture output is produced in the delta as well as 65% of vegetables and fruit [10][50].

2016 was a year of extreme drought in the Mekong River Basin, triggered by El Niño which significantly influenced hydrological processes in the southern and central part of the basin. The national water authorities declared that "the drought has resulted in the decrease of groundwater levels and the most extensive salinity intrusion in last 90 years" in the Vietnamese MKD [84]. The lack of rains caused lower discharges (of approximately 900m^3s^{-1} with respect to the normal dry season discharge ($\pm 3000 m^3 s^{-1}$ Figure 2.2(a)) in the Mekong river. Seawater intruded further inland under tidal influence via the delta's main distributary branches, the Tien and Hau rivers (Figure 2.1) [10]. Salinity intrusion affected the water quality in the canal systems, levels of which were already low due to the drought and high evaporative demand. Without a source of fresh water for irrigation, farmers struggled as their rice crops were damaged or failed.

The salinity intrusion length is indicated by the 4 g/L salt concentration isohaline. In average years, the salinity intrusion reaches a maximum length of 35-40 km in the Hau River around April-May [**?**]. In 2016, salinity expanded much earlier and more extensive through the Tien and Hau rivers up to 45-65 km and 55-60km respectively (Figure 2.1). According to the Ministry of Agriculture and Rural Development, 400,000 ha of cropland in the MKD have been damaged by drought and salinity intrusion, of which 25,900 ha were left fallow. 224,552 ha of damaged rice areas were reported by mid-April 2016 [10], and rice yields dropped by 6.3% due to spoiled crops in 11 of the 13 provinces in the MKD [94].

The process of mixing sea water and fresh water is influenced by topography, river discharge, and tidal propagation. In the dry period, seawater ingresses through drains, creeks, and rivers in the delta [48]. The construction of water management control measures such as dikes and sluices are built to keep the saline water out of irrigation areas. However, many canals have not yet been equipped with sluices to prevent saltwater intrusion [81]. In addition to management issues, several other factors influence the severity of the salinity intrusion. Upstream of the MKD, forests are rapidly being converted into intensive agricultural land and dams are constructed along the entire stretch of the Mekong River, decreasing downstream discharges [7][78][42]. Increased groundwater extraction has led to severe subsidence issues in the MKD [56] which outpaces the risk of salinity intrusion caused by sea level rise [74][78]. In addition, dam construction reduces the supply of fertile sediment to the delta [69], and excessive sand-mining has increased the depth along the Tien and Hau rivers by 5 to 7m since 2008 [2][82]. Consequently, saline water infiltrates groundwater aquifers, and salinity gradients increase in large parts of the MKD, in particular during the dry-season months [78][74]. Moreover, the region is likely to experience a shift in wet and dry seasons and an increase in the duration of the dry season [45].

Rice farmers in the coastal MKD have experienced salinity problems for decades and adapted their farming systems to cope with prevailing conditions. Farmers in the coastal zones responded by implementing a more varied production scheme, including raising shrimp during the dry season and growing more salt-tolerant crop varieties on the banks of their fields [53]. Nevertheless, due to the increased climate variability and anthropogenic pressures, the salinity problems could become more severe and less predictable in the future, limiting farmer livelihoods and threatening food security in the delta. Without taking measures for further adaptation, the impacts and damages caused by the recent extreme drought and salinity event on agriculture production could become the norm for the future.

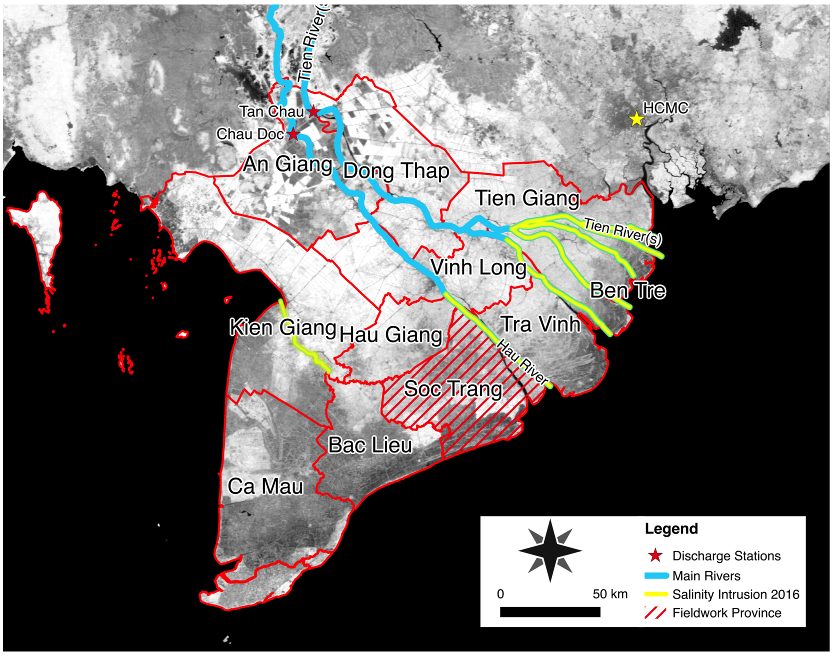

Figure 2.1: Mekong Delta (MKD)

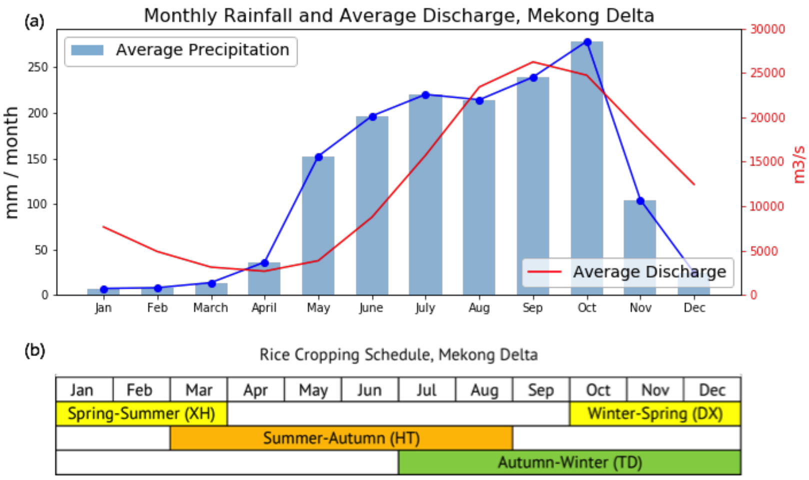

Figure 2.2: (**a**) Precipitation and Discharge MKD (Chau Doc and Tan Chau Stations) [21] (**b**) Rice cropping schedule MKD

Rice is considered a salt-sensitive crop, with a salinity threshold as low as 3 dS/m, or 2 g/L[54] [1]. Even though rice is salt sensitive, it is often grown in areas where saline soils prevail because it grows well under flooded conditions that promote leeching of salts [48]. Salinity tolerance varies with the growth stage of the rice plant (Figure 2.3). Rice is sensitive to salinity at the seedling stage, becomes more tolerant at the late vegetative phase, and is intolerant again at the reproductive phase. The most sensitive rice growth stages occur during emergence, seedling, and booting. Extremely high salt stress or above-optimal salt conditions cause severe damage to plants or even plant death at these stages, whereas moderate salt stress affects the rate of plant growth and reduces most growth and yield parameters [77]. In Vietnam, the farmer reports damages and (lowered) yields to the commune, the local government body, which aggregates yields and damages of rice cultivated areas and transfers this information to higher administrative levels. There is no spatial processing or analysis involved in recording this data, which could serve to gain insight into vulnerable rice areas. Satellite data can be used to monitor rice production and investigate spatial trends over time to support land use planning [43]. In turn, the intensely documented agricultural context of Vietnam could be used to validate remote sensing products and analysis.

This research investigates whether remote sensing can be used to map the impact of salinity on rice production in Soc Trang, an affected coastal province in the MKD (Figure 2.1). Several studies have developed satellite-based salinity indices to detect salinity from bare soil in (semi-) arid environments [23] [25] [5]. These methods are not applicable to monitor flooded rice paddies in the tropics. Performance of rice crop in terms of its phenology can be considered as a proxy to measure the level of salinity stress [66]. Researchers have effectively mapped seasonal rice crops using satellite data [71] [6] [95] [18]. Phenology of rice is well observed from space due to the distinct patterns of flooding and plant development

Multispectral images of satellites consisting of several bands of data offer information on land properties based on its spectral reflectance. Various indices, such as NDVI, EVI, RVI, composed of different spectral bands can be used to accentuate land cover [49]. The Normalized Vegetation Index (NDVI) derived from the near-infrared and red bands can be used to quantify the greenness of vegetation; in this case, the rice crop. The NDVI has the finest resolution among other vegetation indices which apply additional bands of different wavelengths available at a coarser resolution [14]. The NDVI is low at the transplantation stage, increases over the vegetative-to-reproductive stage and gradually decreases with the progression of the ripening stage. When the rice growth phase changes from reproductive to ripening phase, a maximum greenness is measured (Figure 2.3). NDVI time series can thus be used to interpret the seasonal cycle of rice growth [71]. The index has also been used to estimate rice yield before harvesting [59].

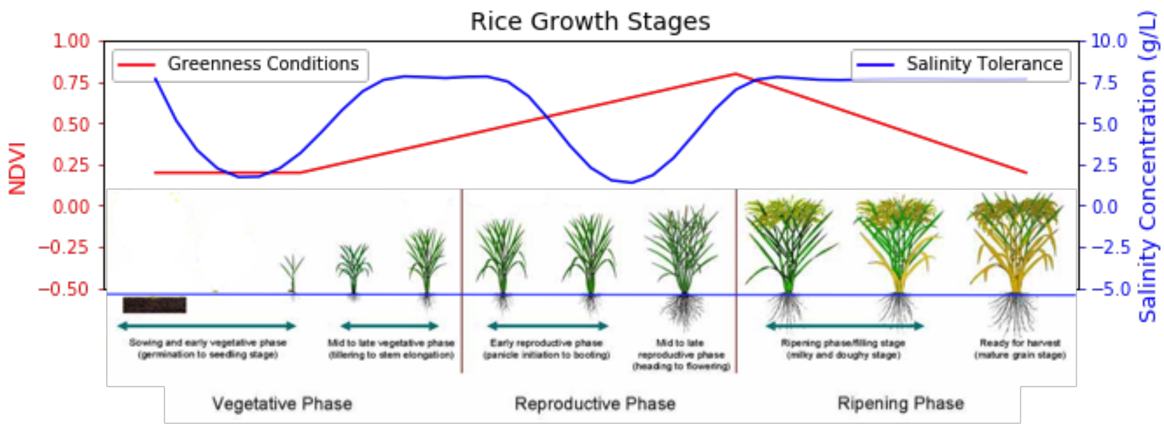

Figure 2.3: Growing stages of a rice plant. The red line shows a typical temporal dynamics of NDVI or associated greenness conditions. The blue line indicates the tolerance level of the rice plant to the salinity concentration of the irrigation water. Figure adapted from [59], [77],[44], and [1]

In tropical regions such as the MKD, optical data often suffer from cloud contamination. Moderate resolution satellite systems such as MODIS have daily revisiting cycles which decreases the chances of cloud interference during earth surface monitoring. Because MODIS has the appropriate spectral bands and temporal resolution needed for crop identification and phenological monitoring at regional scales [61], its data are used by many rice researchers in cases in Asia [71] [95]. In the MKD, spatial-temporal rice cropping patterns are generally homogeneous at the commune level. By synchronizing seeding and harvest time, pest and disease damages can be reduced, local water management more easily controlled and logistics around harvest efficiently organized [64]. Individual rice fields in the MKD (0.5 ha on average [51]) are usually regrouped into large units as rice cultivation is often organized by cooperatives of several farmers [6]. Therefore, MODIS' 250m resolution is appropriate to monitor rice production in Vietnam.

Nguyen et al. (2012) successfully estimated the spatial and temporal patterns of rice grown in the MKD with a 94% overall accuracy [64]. With an unsupervised classification algorithm and using the divergence separability indices of NDVI classes, prevailing rice cropping patterns could be mapped using 10-day SPOT NDVI image series. Sakamoto et al. (2009) used MODIS moderate resolution surface-reflectance 8-day composite data to detect the expansion of intensive farming systems (shrimp farming and triple rice cropping) in Soc Trang and Bac Lieu provinces of the MKD [72].

While monitoring phenology of the rice plant, anomalies can be detected when the NDVI departs from a long-term average. Since hampered rice growth development can be related to several factors such as drought, soil or salinity problems or changes in crop management practices, it is important to collect ground data for verification. In a recent review of the application of remote sensors in mapping rice areas, Mosleh et al. (2015) identified the need for studies which “evaluate the potential of applying multi-year remote sensing data for quantifying inter-annual variations of rice fields and its production due to extreme climate events (e.g., flooding, drought, cyclone, etc.) and/or human-driven land use changes [59].” Using MODIS NDVI time series, the value of mapping the impact of salinity intrusion on rice productivity is explored in this study.

3

Materials & Methods

3.1. Study Area

The target area of this study is the coastal province of Soc Trang in the Vietnamese MKD (Figure 2.1(a)). Due to the tropical savanna climate [68], the monthly average temperature does not drop below 25 degrees Celsius during the year and the average annual precipitation lies around 1660mm [21]. The south-west monsoon (Gio Chuong) causes heavy rainfall from May to November and the decrease in precipitation in December marks the beginning of the dry season, which lasts through April [72] (Figure 2.1(b)). Average discharge values range from about $3,000$ to $26,000 m3/s$ from low flow to high flow as measured at Chau Doc and Tan Chau stations (Figure 2.1(b)), reflecting the remarkable hydraulic dynamics of this region.

Problems with salinity begin when little rainfall accumulates in the first months of the year and the Mekong river flow is low. Salinity concentrations usually peak around April and May and vary with the location in the province (8 salinity measurement stations, Figure 3.1). In 2016, salinity intrusion occurred much earlier and more extensive in Soc Trang province than normally. The authorities declared a natural disaster emergency after many hectares of winter-spring rice crops in the MKD were "seriously damaged" [87].

There are seven different irrigation systems in the province of Soc Trang that ensure water quality and quantity (Figure 3.1). Depending on the availability of water and location in the province, different farming systems can be found such as triple cropping rice, double cropping rice, rice-shrimp rotational farming, orchards, vegetables, and brackish aquaculture. The cropping schedules for rice vary across the province; growing seasons are named according to the timing in Figure 2.1(c).

The income of farmers in the MKD depends significantly on the weather conditions. For rice farmers, winter-spring (DX) is the most profitable crop of the year as the weather is usually favorable. The high number of sunshine hours and relatively dry period prevents pest and disease outbreaks. In triple rice crop areas, the third rice crop (Spring-Summer (XH)) generally has the lowest output [17]. Besides drought, flooding of fields due to intense rainfall can cause damages in the rainy season. Growing rice is considered a sustainable practice compared to aquaculture, which includes higher risk and profits. Income from aquaculture is on average 7x higher for extensive shrimp farming (Black Tiger Shrimp, 5 shrimps/m^2) and 30x higher for intensive shrimp farming (White Leg Shrimp, 25 shrimps/m^2) per hectare as compared to income from rice production. However, investment costs are high and shrimp can catch diseases quickly which often results in total production failure. In rice-shrimp rotational areas, farmers grow shrimps on their fields in the dry season when there is a shortage of fresh water. Rice yields are usually lower but farmers have on average due to the profitability of aquaculture [17]. To switch from shrimp to rice production, the farmer washes the salt water from the farm using the first rainfall. Farmers often grow vegetables on the banks of their fields to make more income. Other additional sources of income include livestock production such as pigs and ducks and selling goods from small house shops.

Surface water from the canal system is the main source of irrigation water for farmers, who use pumps to supply their fields. The law on water resources (17/2012/QH13) imposes strict regulations on the use of groundwater for aquaculture production in the coastal zone [81]. Groundwater may be used for vegetable production in the brackish irrigation zones, whereas diluting salt concentrations in aquaculture ponds is restrained. Nevertheless, researchers confirmed the MKD subsided by 18 cm in the last 25 years on average due to excessive groundwater extraction [56].

Farmers' activities are closely monitored and supported by the commune, the local government body, where farmers report on their rice production on a weekly basis. The national government centrally plans Vietnam's agricultural objectives. In every province, the plans are detailed to suit the farmers and area. In Soc Trang, the farmer is free to decide what crop he/she wants to grow and when. The responsible provincial department (Department of Agriculture and Rural Development (DARD)) encourages farmers to grow certain crops or farming systems by model [17].

3.2. Data

3.2.1. Remote Sensing

MODIS is a multispectral optical sensor mounted on the NASA Earth-observing satellites EOS AM (Terra) and EOS PM (Aqua). The wide observation swath of MODIS (2330 km) makes it possible to acquire images of the MKD twice daily. After geo-referencing, atmospheric correction and image enhancement (such as cloud masking) pre-processing steps, the red band (1) and near-infrared band (2) are used to calculate the NDVI for each acquisition according to the formula: $(NIR-RED)/(NIR+RED)$. 14 NDVI images are stacked for each week and averaged to retrieve the mean NDVI value. Images on cloudy days are not included. An NDVI time series for each 7-day period is available from 2001 until today with a resolution of 250m. This approach is similar to the construction of a Maximum Value Composite (MVC) from multi-temporal NDVI images [40].

MVCs suffer from significant residual effects [40]. Mathematical filters can be applied to reduce noise and to reconstruct high-quality smoothed time-series of NDVI data for further analysis [36]. Many time-series smoothing methods (f.e. Savitzky Golay fitting and Spline smoothening) are successfully used for reducing noise and extracting plant phenological parameters from remotely-sensed data, but there is still no conclusive evidence in favor of one method over others [9].

In this study, the Kalman filter is applied, which is an algorithm that smooths noisy data and provides estimates of parameters of interest [31]. The designed Kalman filter looks at the input data with a 9-week moving window (+/- 4 weeks), and assigns appropriate weights to the weekly NDVI input value using the number of valid MODIS acquisitions (0-14) within that weekly product. When this number is low due to cloud interference, the NDVI value for that week is given less value in the calculation of the smoothed NDVI result. The Kalman filter combines a forward and a backward recursion to estimate a state based on data from both previous and later times [76]. The end of the time-series states, which are future data observations, are predicted.

The Kalman filter is applied in this study for its high ability to fine-tune the filter and to handle sparse data [73][75]. Weights can be assigned to input data and values at the end of the time-series can be predicted. The filter works without lag. The Kalman algorithm is available in an open-source python implementation; thus integration in processing chains is simple [75]. Within a multitude of applications, Kalman filter algorithms have been applied to monitor crop phenology [86], specifically rice [85] [14].

In addition to MODIS NDVI time-series, SENTINEL-1 imagery from 2015 is used as an additional input for the classification of land use in the province (section 3.3.1). Radar observations can improve classification results as microwaves penetrate the canopy and detect surface water in mangrove areas, which results in an enhanced distinction between forest types.

The peak detection algorithm (section 3.3.2) uses NDVI and flood index time series as input data. The flood index is created using eight different bands in the formula: $(RED+GREEN-SWIR3)/(NIR*SWIR1*max(BLUE, 0.005)))*(RED/NIR))$. The flood index is designed to detect flooded rice paddies and preferred over the Normalized Difference Water Index (NDWI), which works better for deep water than for shallow water detection. NDWI is also more sensitive to detect haze and bare areas such as sands and river banks which interferes with water detection [75].

3.2.2. Ground Data

Fieldwork was conducted in the MKD during a period of two months from March through April at the peak of the dry season in 2017. Twelve communes were visited in Soc Trang province. These were selected on the basis of expected land cover differences and applied farming systems. Information was gathered through interviews with commune officials and affected farmers. Thirty farmer surveys (Appendix A) were completed through which information about rice growing schedules, yields, income and salinity impact was obtained. Coordinates of visited farmers' fields were taken, as well as occurrences of different land cover classes (± 800 points) around the province. Two interviews with the DARD of Soc Trang were conducted at the start and end of the fieldwork period. Besides valuable insight, documentation on affected rice areas (Appendix

F) and salinity measurements for eight different stations in Soc Trang Province (Figure 3.1) were provided in those meetings. Salinity concentrations in mg/L with a two-hour temporal resolution are available from January until June for 2014, 2015 and 2016. The maximum salinity concentration under tidal influence for each day is retrieved. Affected rice areas are subdivided in damaged hectares according to percentages in the documentation; less than 30% (ha), between 30% (ha) and 70%, more than 70% (ha).

3.3. Methods

3.3.1. Classification

Ground data are used to produce a training map with 12 different land use classes, such as rice areas, forests, and urban settlements. This training map is used in a supervised classification of MODIS satellite images, implemented by the eXtreme Gradient Boosting algorithm (XGBoost). The fundamentals of this technique lie in machine learning which uses an optimization algorithm on an objective function [79]. In this case, the objective function is how well the model can predict land cover classes, given the signatures of the training map. XGBoost implements gradient boosted decision trees designed for speed and performance [8] and currently outperforms other implementations of gradient boosting in machine learning in benchmarking tests [65]. Decision trees create a model that predicts the value of a target variable (the land cover class) by learning simple decision rules inferred from training data features [67]. Gradient boosting is an ensemble technique where new decisions trees are added in additive optimization of the objective function to correct the errors made by existing models. Available as an open source package, the scalability of XGBoost is due to several optimizations; XGboost incorporates a regularized model to prevent overfitting and simplifies the objective function and algorithm for parallelization. Moreover, a novel tree learning algorithm to handle sparse data is applied [13] The theory behind the applied XGBoost software is further explained in Appendix B.

The NDVI time series of 2015 is used as input data for the classification. To improve mangrove forest classification, three SENTINEL-1 radar composites are added to the input data. The composites are composed of three bands of data which contain averaged values from stacked radar images of 2015; (1) composite of VV polarization with minimum, mean and maximum value backscatter, (2) composite of VV polarization (min-mean-max) backscatter and (3) composite of mean VV, mean VH and the difference of both polarizations (VV-VH) backscatter. Once the rice areas with different cropping schedules are located, the temporal signal variability of the NDVI for the different rice classes are investigated by calculating the mean and standard deviation of 5 years of data. The result gives insight into the climatology for these rice areas.

3.3.2. Peak Detection

A peak detection algorithm is used to retrieve dates of peak NDVI values in order to characterize the temporal and spatial variability in the timing of maximum greenness in the different rice seasons. A maximum NDVI and the change in NDVI slope from positive to negative characterizes the heading and flowering growth stage of the rice, whereas, at harvest, the NDVI slope reaches its minimum value [89]. To delineate rice areas and count rice seasons, threshold values for minima and maxima are established.

A pixel is considered to be flooded when the flood index time series contains a flood index level above zero and the NDVI value is below 0.2. If a pixel is not flooded, the thresholds for maxima and minima of a rice season are applied. When a detected maximum is higher than the specified NDVI threshold of 0.6, it registers as the peak of a rice season. Similarly, when a detected minimum is lower than the specified NDVI threshold of 0.5, it registers as a valley of a rice season. A minimum threshold of 0.15 is set as a required difference between the NDVI value of the peak and start of the season. Thresholds are selected for operational suitability to map rice areas from distinct other land use classes, after evaluating a multitude of different rice growth curves in the MKD.

The input data is evaluated over a period of 82 weeks to capture the seasonality of rice growing seasons during one year, including those which start in previous years and end in consecutive years. When the peak-finding algorithm registers two consecutive peaks, the time between the peaks should be between 13 to 26 weeks, representing the plausible lengths of growing seasons for different rice varieties. The peak date of each rice growing season is registered for each pixel. Up to a maximum of four rice seasons can be detected. The peak dates are plotted in a histogram for seven consecutive years that precede the salinity intrusion event of 2016. Histograms are generated for each district in Soc Trang (Figure 3.1) to capture regional differences in rice cropping schedules.

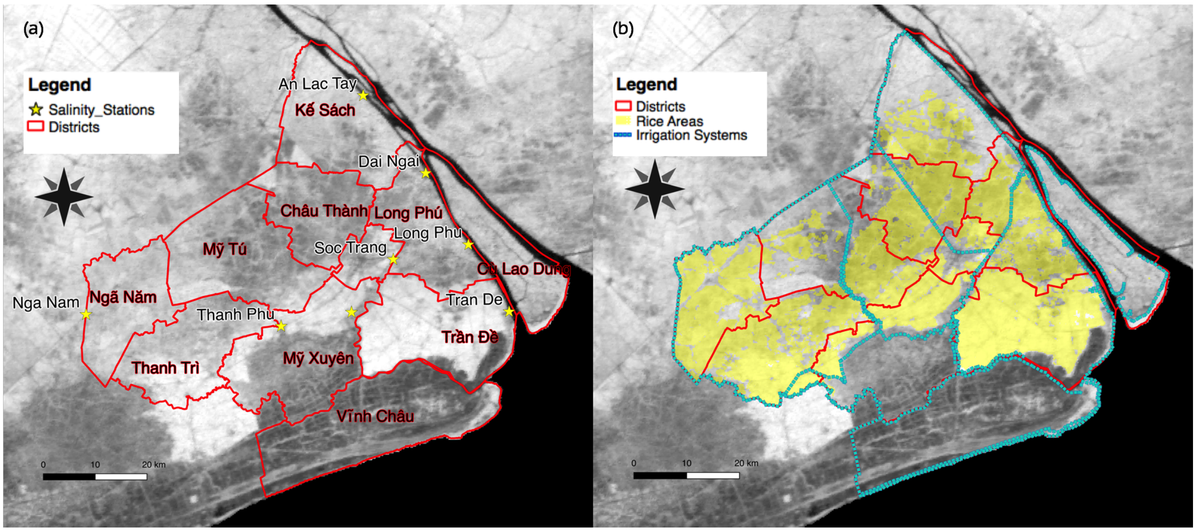

Figure 3.1: (a) Districts and salinity stations (b) Irrigation systems and rice areas, in Soc Trang Province

3.3.3. Anomaly Detection

Comparing rice development in 2016 against development in years without severe salinity intrusion could point to locations where high salinity concentration posed problems for rice growth. Five years of multitemporal NDVI series from 2011 to 2015 are averaged to obtain the climatology or baseline growth curves of rice areas. Anomalies in rice growth can be detected by comparing NDVI development in 2016 against the climatology. At each timestep, NDVI values are evaluated with a 5-week averaging window, to capture trends in peaks and limit the influence of smaller deviations. A positive anomaly means a lower value of NDVI in 2016 compared to the years before, which is indicated in Figure 3.2.

The cumulative distribution of anomaly values at the given time step is inspected and a threshold anomaly NDVI value established at the deflection point of the CDF curve. Anomaly areas with NDVI values above this threshold are used in further analysis. To relate the anomalies above the threshold with a negative impact of salinity on rice growth, specific areas were investigated in their spatial context with collected ground data and soft information. This information can be used to rule out other factors that may cause anomalies, such as management decisions which could cause reduced or delayed rice growth. NDVI time series for anomaly areas above the threshold are investigated and may be used to confirm the mechanisms at work. Extracted areas are overlain with administrative boundaries of Soc Trang province and compared with tabular information on affected rice hectares obtained from DARD and visited communes during fieldwork.

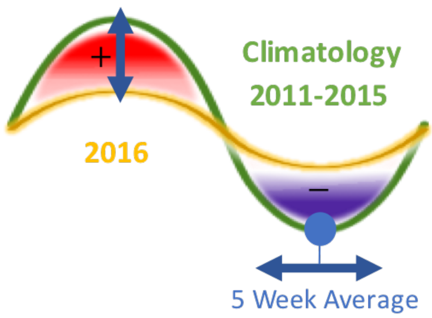

Figure 3.2: Anomaly Approach. Comparing 2016 NDVI time-series against a climatology

4

Results & Discussion

4.1. Classification

Figure 4.1 shows the results of the land use classification of Soc Trang Province. Rice areas were divided into three classes depending on growth cycles and timing during the year. The island of Cu Lao Dung is solely planted with sugarcane crop. In the coastal areas, aquaculture is produced along with vegetable farming (onions) in Vin Chau district. In the northeast district, Ke Sach, fruit trees are farmed. Melaleuca, peat and mangrove forest can also be found in Soc Trang province.

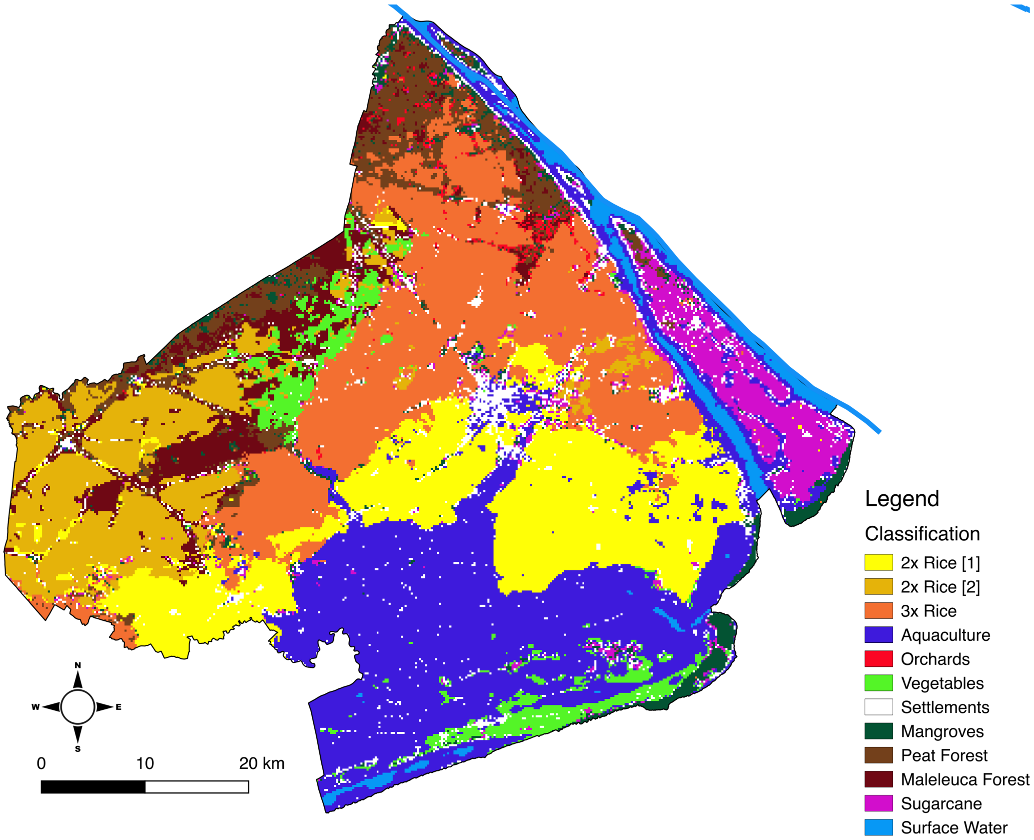

Figure 4.1: Land use Soc Trang province, 2015

Rice production covers the majority of land in the province. Averaged NDVI time-series over five years of the three different rice classes are shown in figure 4.2, including variability within the classes. Increased variability at a given time step can be related to changes in the timing of the seeding of rice, or in some cases, changes in cropping cycles. Schedules differ for double cropping rice areas in Soc Trang; schedule 4.2(b) appears predominantly in the East and schedule 4.2(c) in the West of the province. NDVI values considerably deviate from the mean around week 44 and 45 in areas with a 2x Rice [2] rice cropping schedule. The deviation can be ascribed to less-defined, misclassified 3x Rice areas as explained in Appendix C.

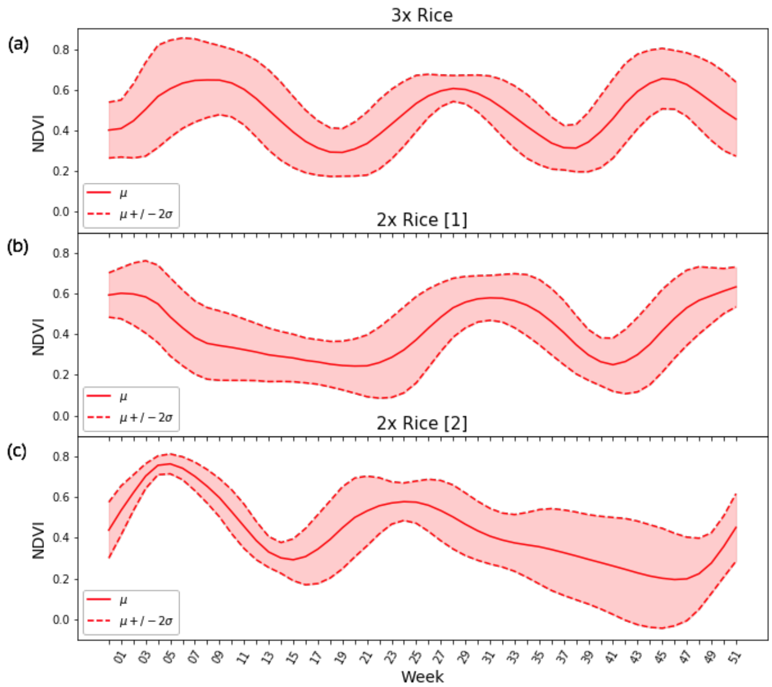

Figure 4.2: Climatology of rice areas with different growing schedules (**a**) 3x Rice (**b**) 2x Rice [1], (**c**) 2x Rice [2]. NDVI time-series from 2011 to 2015 are averaged for each grid cell within the rice class. μ is mean value of all grid cells at a given time step. σ is the standard deviation of this distribution. The shaded area is the 95% confidence interval.

4.2. Peak Detection

Peak detection was applied to discern different rice cropping cycles. Figure E.1 shows how dates of maximum NDVI are heterogeneously spread throughout the province as rice crop scheduling greatly varies at this scale. Within districts, however, more homogeneous timing of peak dates appear because different cropping schedules for rice mainly depend on the irrigation system and the available water during the year. Communes within the district try to combine farmers into groups to get large areas to grow the same crops at the same time. This way, pest and diseases can be avoided and rice is efficiently sold afterward. Figure 4.3 demonstrates the peak rice growth dates for Long Phu (a) and Nga Nam (b) district for five years of NDVI time-series, including the climatology. Results for the remaining rice producing districts are presented in Appendix E.

The results from the classification and the peak detection algorithm were compared, as no detailed digital land cover map of Soc Trang was available to validate the results. The two different double cropping rice areas from the classification results are combined into one 2x Rice class for comparison with the peak detection results. The confusion matrix is presented in table 4.1. 81.6% of rice grid cells overlap. The error percentage of 18.4% stems predominantly from 7.2% of grid cells classed as rice areas by the peak detection algorithm instead of non-rice as classed by the classification (Figure D.2). The peak detection algorithm registers parts of the Melaleuca and peat forest area as rice as well as some urban areas along roads, as can be seen in Figure D.1(b) and the land use classification results in Figure 4.1.

4.3. Anomaly Detection

Anomalies were identified at week 6 and 21 in 2016. The two cases are named according to the administrative district where most impact on rice crops is observed.

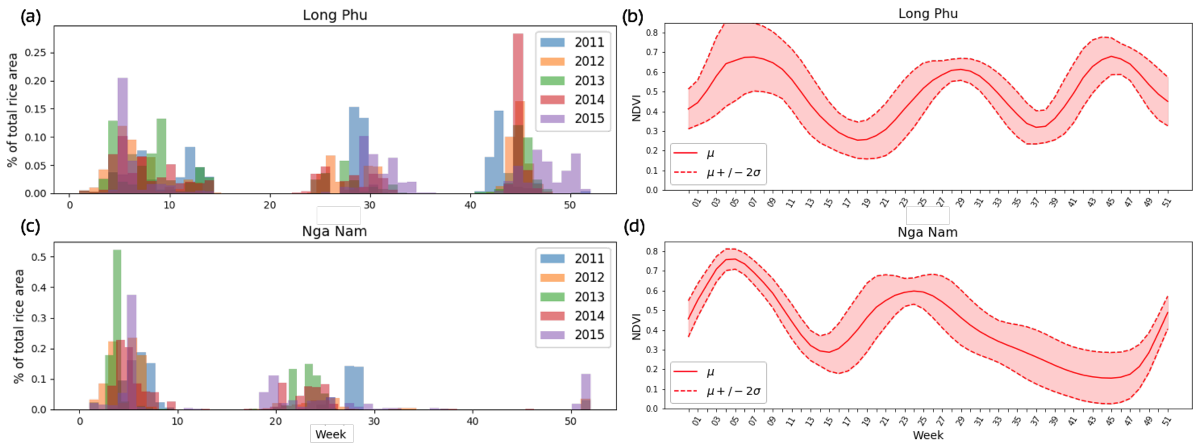

Figure 4.3: NDVI peak dates for rice areas of (**a**) Long Phu and (**c**) Nga Nam district and corresponding climatologies (**c**,**d**) from 2011 to 2015

		Peak detection		
		Non-Rice	**2x Rice**	**3x Rice**
Classification	**Non-Rice**	43.9%	7.2%	2.8%
	2x Rice	2.8%	22.3%	1.5%
	3x Rice	0.5%	3.7%	15.4%

Table 4.1: Confusion Matrix

4.3.1. Winter-Spring rice in Long Phu district

The red areas in Figure 4.4(b) highlight the rice areas where growth in 2016 was limited compared to the average growth of the preceding five years (Figure 4.4(b)). The threshold is placed at the 95% percentile, two standard deviations above the mean value of the anomaly distribution (0.254, Figure 4.4(c)). Most of the detected anomalies above threshold lie within the district of Long Phu. Figure 4.3 shows how the first rice season 'Winter-Spring' peaks in January and February in this district. Figure 4.4(d) shows the absence of the Winter-Spring rice season between week 4 and week 12 (February and March) in 2016.

Two communes were visited in Long Phu district; Long Duc and Truong Khanh commune. Long Duc commune reported that agriculture was affected by salinity during four months. 600 hectares of rice fields were 100% damaged as the Winter-Spring (DX) crop was lost in totality. Analysis with MODIS NDVI data outlines 585 hectares of lower rice productivity within this commune. Visited farmers recounted how rice yields were low due to a lack of fresh irrigation water early 2016. Winter-Spring is usually the most profitable growing season and yields above 7000 kg/ha can commonly be obtained. Early 2016 was different, as Winter-Spring rice yielded a mere 1500 kg/ha in an extreme case. Many farmers suffered significant losses as investment costs of planting rice seeds had already been incurred at the onset of the salinity event.

Truong Khanh officials reported yields had dropped from 8 ton/ha in 2015 to 2 ton/ha in 2016 due to salinity problems. The commune recorded 468 ha of rice fields damaged between 30-70% and 263 ha above 70%. In this commune, the detected anomalies cover an area of 207 ha. DARD proclaims an aggregated 4742 ha of damaged rice area in Long Phu district, of which 3211 ha is affected more than 70%. Our analysis flags 7263 ha of potentially damaged rice fields at district level. Table 4.2 presents the analysis of damages rice fields in percentages of total surface area.

The affected areas are located within two irrigation systems which are connected to different intake channels starting at Dai Ngai. Figure 4.5(a,b,c) presents daily salinity measurements from An Lac Tay, Dai Ngai and Soc Trang stations, which are located in the Hau River and Song Dihn Channel (Figure 4.6). Salinity concentrations in 2014 can be viewed as a 'normal year' baseline, whereas recorded values in 2015 were already higher than usual. Values exceed the salinity intrusion length concentration of 4 g/L in the middle of January in 2016 in the inland river channel of Song Dihn and remain high until May/June.

Interviewed farmers and government officials report that leakages through the water management system caused salinity intrusion due to the system's poorly maintained dikes and sluice gates. The sluice gates were closed at the time of salinity intrusion, and the operation by the local irrigation department considered

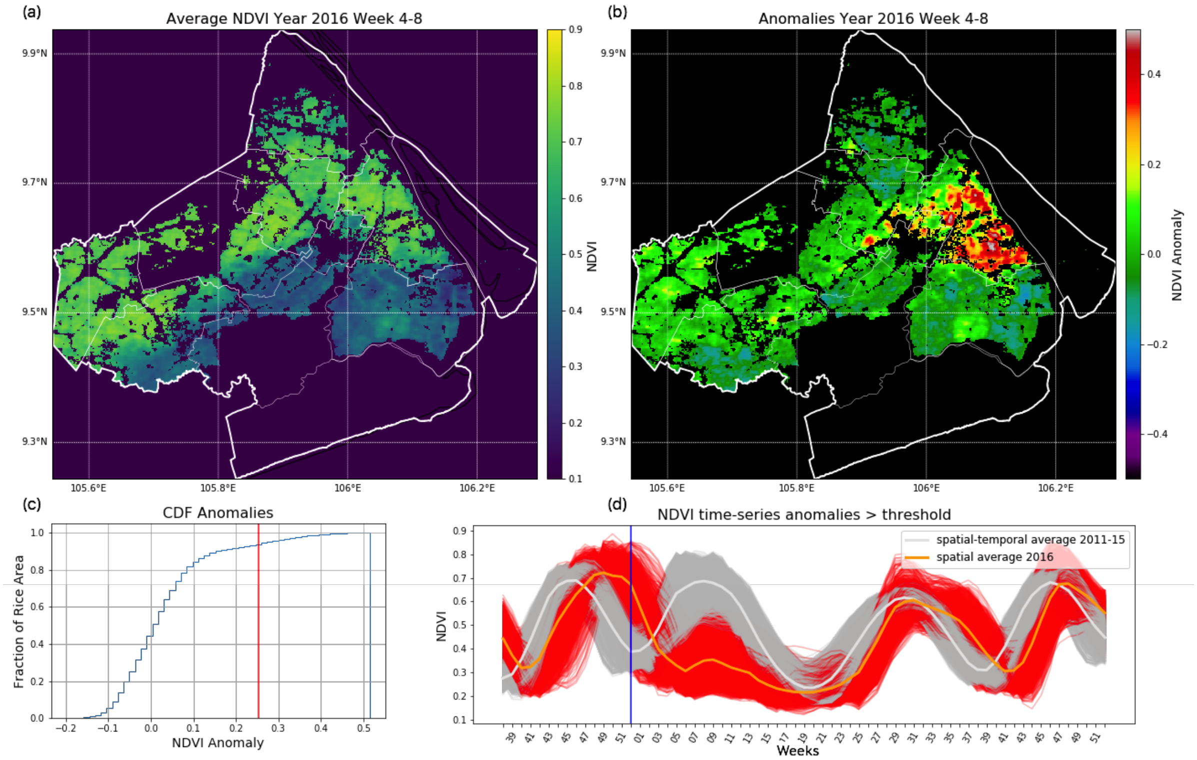

Figure 4.4: 'Long Phu' (**a**) Climatology (**b**) Anomalies (**c**) CDF of Anomalies (**d**)' NDVI time-series of Anomalies above threshold value

adequate. Salinity intruded earlier and further into the Hau River in 2016 compared to normal conditions. At the height of Ke Sach district, north of Long Phu district, salt water flowed into the irrigation system as there are no sluice gates at this height (Figure 4.6(a)). Ke Sach district has a large orchard area which is not directly affected by salinity such as rice. Salinity is taken up by the trees and effects are visible only six months later as explained by the local authorities responsible for aggregating salinity damages. Once the saline water protrudes beyond the intake point, a complex network of irrigation channels spreads the brackish water throughout the water management system depriving local farmers in the extended region of a fresh water source.

		Affected rice (ha) (% of total area)		
Cases	**Administrative**	**Government Data**	**Satellite Data Analysis**	**Total Area (ha)**
'Long Phu'	Long Phu (D)	4742 (17.7%)	7263 (27.1%)	26797
	Long Duc (C)	*600 (20.0%)*	*585 (19.5%)*	*3003*
	Truong Khanh (C)	*731 (23.5%)*	*207 (6.6%)*	*3110*
'Nga Nam'	Nga Nam (D)	975 (4.0%)	6594 (26.8%)	24582
	Vinh Bien (C)	*700 (20.5%)*	*2325 (67.9%)*	*3422*
	Long Bien (C)	*100 (3.4%)*	*772 (26.5%)*	*2908*

Table 4.2: Comparing affected rice areas, D = District, C = Commune

4.3.2. Summer-Autumn rice in Nga Nam district

When moving through time, our analysis reveals inhibited rice growth from week 19 to 23 in 2016 as seen in Figure 4.7(b). This timing corresponds with the Summer-Authumn rice season (Figure 2.1) and coincides with a period of maximum detected peaks in Nga Nam (Figure 4.3) and Thanh Tri district, in which the detected anomalies above threshold are located. The threshold is placed at the 95% percentile, two standard deviations above the mean of the anomaly distribution (0.265, Figure 4.7(c)). When looking at the temporal development of the NDVI series at these locations in Figure 4.7(d), we see a delayed start of the rice growing season around May 2016. This delayed seeding of rice can be attributed the extended presence of high salin-

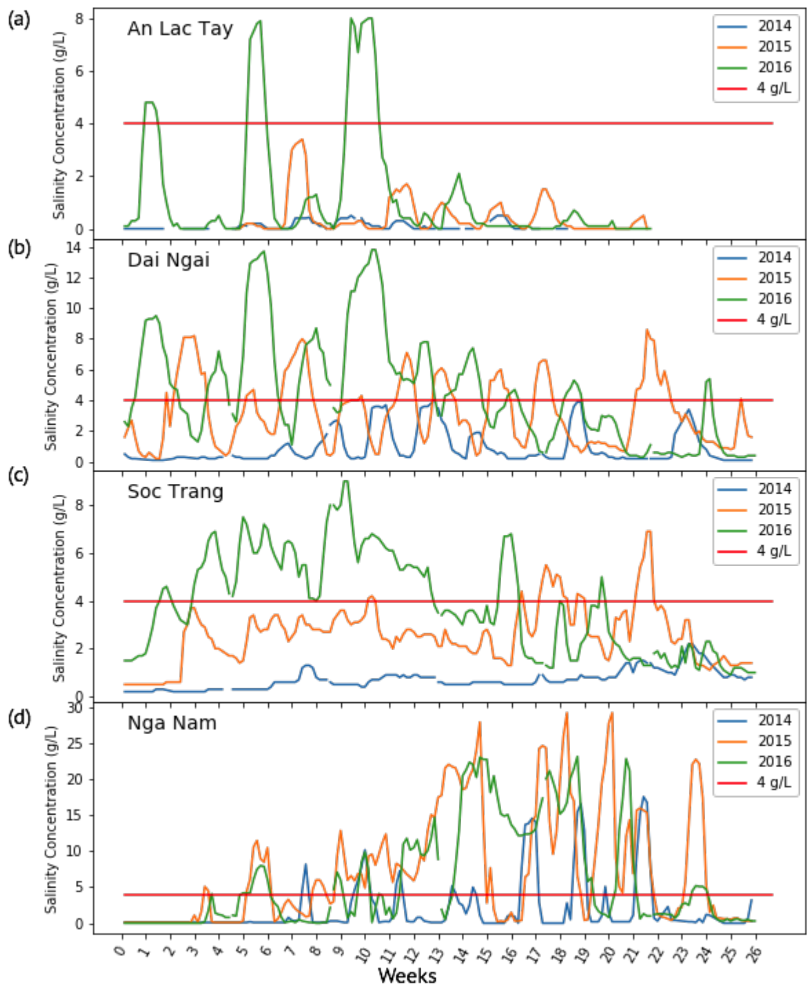

Figure 4.5: Daily Maximum Salinity Concentrations measured at (**a**) An Lac Tay, (**b**) Dai Ngai, (**c**) Soc Trang and (**d**) Nga Nam Station

ity concentrations in the canal network and the decision of farmers to wait for the rains to dilute the canals and flush the system with fresh water before planting their Summer-Autumn rice season.

DARD specifies 975 ha damaged rice fields in Nga Nam and 117 ha in Thanh Tri district. However, this area was reported on June 10th (week 23). As Summer-Autumn rice is harvested until the beginning of July in Nga Nam district (Figure 4.3) and measured salinity records show still a salinity concentration above 4 g/L (Figure 4.5(d)) at this date, the area may be a conservative estimate of the total affected area. This may also be a reason for discrepancies between collected ground data in Nga Nam Communes (table F.1) and the aggregated values obtained through DARD (table F.2). For example, when visiting Vinh Bien commune in Nga Nam district in April 2017, officials stated that salinity had affected 700 ha of rice in 2016. This reported area already constitutes a significant fraction of the total affected area in Nga Nam district as reported by DARD. The anomalies detected by our research span an area of 6,594 ha in Nga Nam and 2,527 ha in Thanh Tri districts. Comparing affected areas is not applicable in this case (table 4.2), as Figure 4.7(d) shows no decrease in peak NDVI and the aggregate area can be mostly contributed to a delay in onset of the rice season.

The district Nga Nam faces salinity intrusion from two directions. From the coastal province Bac Lieu, which has large-scale aquaculture production, Phung Hiep Highway canal transports brackish water into Soc Trang province (Figure 4.6(b)). Nga Nam district collaborates closely with the units in Bac Lieu to ensure that only diluted salt water enters the rice fields. Because of the established communication between the provinces, the rice farming is usually not affected that much by salinity. Located north-west of Soc Trang is Kien Giang province, which holds the largest area of rice paddy affected by drought and salinity intrusion in 2016 in the MKD [10]. Also from this direction, saline water flowed from the West Sea through Kien Giang all the way to Nga Nam town.

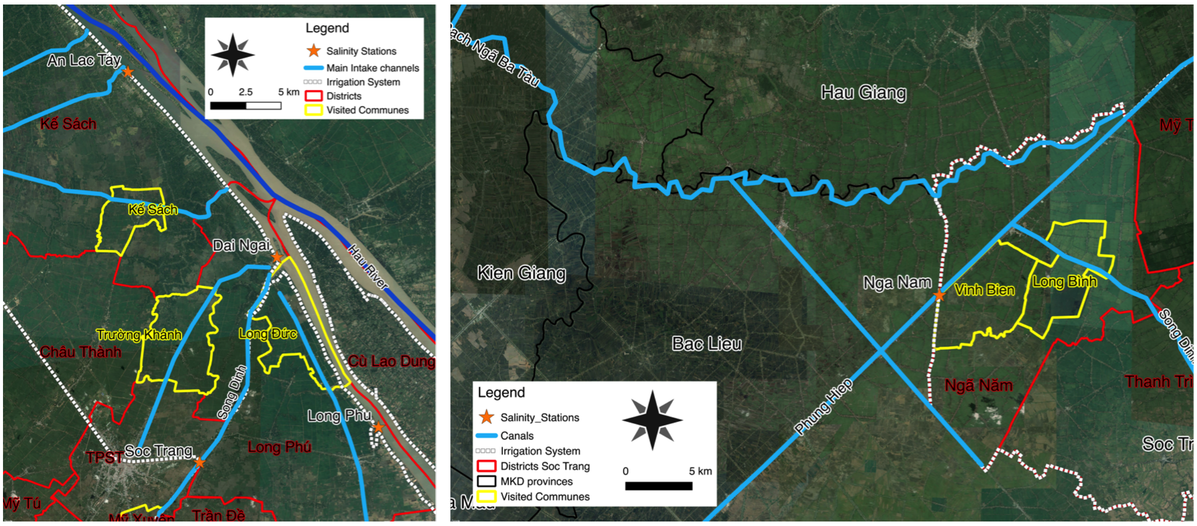

Figure 4.6: Detailed map (**a**) Long Phu and (**a**) Nga Nam districts

Rice Season	**HT (2015)**	**HT (2016)**	**DX (2016-2017)**
Yield of wet rice (kg / ha)	5520	2910	6690
Price of dry rice (VND / kg)	4813	4800	6025

Table 4.3: Average yields of affected farmers in Nga Nam district (from collected farmer survey data)

All eight farmers interviewed across communes of Nga Nam district explained their Summer-Autumn (HT) rice season was affected by salinity to some degree in 2016 (table 4.3). Some farmers stated they planted rice late to avoid irrigating with saline water but consequently suffered as heavy rains inflicted damage upon their crops. The availability of fresh water had not been a problem up until 2-3 years ago in the district; since then, the risk of salinity intrusion increased until maximum heights in 2016. Farmers also reported lower obtained yields in 2015 due to salinity problems, but to a lesser extent. Records from DARD show fluctuating salinity concentrations measured at Nga Nam station (Figure 4.5(d)) for 2015 and 2016, displaying the local exposure to the inflow of brackish water from different directions.

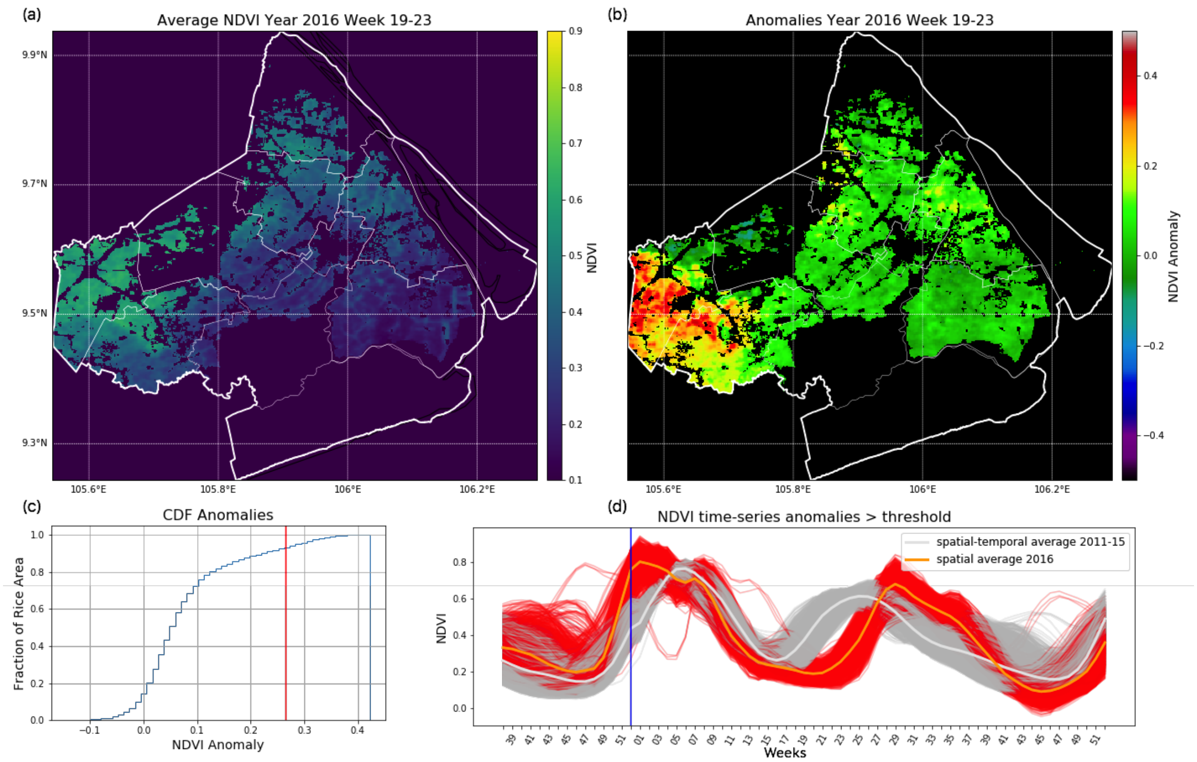

Figure 4.7: 'Nga Nam' (**a**) Climatology (**b**) Anomalies (**c**) CDF of Anomalies (**d**) NDVI time-series of Anomalies above threshold value

5 Conclusion

In this study, we explore the value of mapping the impact of salinity intrusion on rice production in Soc Trang province using MODIS NDVI time-series and collected ground data. Rice areas in the province are mapped first by applying supervised classification and a rice peak detection algorithm. Distinct rice cropping schedules appear within district boundaries using peak detection analysis. Compared against an evaluated climatology for the province, our analysis shows decreased rice growth at two 'hotspots' ('Long Phu' & 'Nga Nam') during 2016. Ground information collected from farmers and local government officials confirm that rice growth was hampered due to salinity problems. In Long Phu district, farmers lost their most profitable crop of the year as their Winter-Spring rice yields decreased. NDVI time-series show a delayed Summer-Autumn rice growth in 2016 in 'Nga Nam' where farmers reported decreased rice yields compared to years before and some waited for a decline in salinity concentrations before sowing.

The approach to detect anomalies set out in this research is valuable to signal problematic rice growth. Whether these anomalies represent areas of salinity-impacted rice productivity, can be confirmed with information and understanding of (local) salt-intrusion mechanisms. Independent information, in the form of ground reference data or salinity modeling, is necessary to attribute the cause of anomalies to salinity. Relating satellite detected hampered rice growth to causes of salinity is highly plausible, if the mechanism of salinity intrusion is understood well. This way, MODIS satellite data can be applied to identify salinity affected rice areas in other delta regions. Shifts in timing of different phenological phases in plants or decrease and increase in rice cropping cycles connected to climate change and agricultural management can directly be mapped with MODIS NDVI time series, as this research shows.

Reconciling affected rice areas as delineated by the method set out in section 3.3.3 and affected rice hectares obtained from the local government is difficult. The government records damaged rice areas in hectares per administrative unit and details damages in different percentages, addressing the extent to which a farmer's rice yield was lost. Areas calculated with remote sensing are measured in units of grid cells with a 250m resolution which represents a reduced NDVI value compared to normal. Because of the fundamental differences in collection of data and reporting damages in different units, it is hard to validate hard data with soft data. We can interpret objective remote sensing results qualitatively. When impact is observed, NDVI time-series of positive anomaly values above threshold need to be checked to determine whether lower rice productivity or a shift in timing of rice growth is present. The resolution of the satellite determines how well we can qualitatively estimate the affected area. Results from analysis with MODIS data at a resolution of 250m can be too coarse to compare affected hectares at this provincial scale, and the approach would better fit a Mekong Delta-wide study.

Several other issues have influenced the results. The NDVI saturates at high biomass and implicates precise monitoring of rice development at certain growth stages [80] [35] [89]. The relation between the greenness condition, detected maximum NDVI, and lowered productivity level (%'s of yield affected rice areas) has not been extensively analyzed. Extremely high salt stress conditions kill the rice plant but moderate to low salt stress affects the plant's growth rate [44]. Efforts in relating parameters of delays in phenology and reduction in potential of photosynthetic activity with salinity stress using satellite data show potential [66], but further studies are required to test the approach on a larger scale and for different environments. Besides this, reported affected rice areas in other regions as aggregated by the provincial government (table F.2) do not 'show up' as anomalies, where impact was expected. Inaccuracy or bias in the obtained tables of damaged rice hectares is non-traceable however. Conflicting collected information and the compiling date of obtained records gives reason to doubt the values used for validation.

Furthermore, applying the Kalman filter to smoothen the NDVI time-series could have reduced the ability to deduce information about the impact of salinity stress on vegetation, or specifically, on photosynthetic activity. The filter is designed to detect the growth stage of the crop near real time. Running the Kalman filter on daily acquisitions would improve NDVI estimates but requires extensive computation power. Because cloud cover rarely persists more than two weeks in South East Asia, the 9-week moving window of the filter captures activity at land surface satisfactory. Weight assignment (0-14) on the quality of acquired satellite images improves filter results so that seasonal trends in crop growth curves become visible without being affected by errors of false acquisitions. It is recommended to compare the results of this research against analysis with non-filtered or differently filtered NDVI time-series. Also, the subsequent peak detection approach on the smoothed time-series includes fixed thresholds which determine rice seasons. The production of flexible thresholds which are locally adapted and related to the seasonal amplitude of the individual pixels could allow for improved rice peak detection [4].

Improved results may also be obtained when the anomaly detection method is applied on different sources of data. Since April 2016, ESA's SENTINEL-1 acquires '5mx20m' resolution radar images of the MKD at a regular interval of seven days [27]. Without cloud interference, this radar data has a high potential for mapping rice-cultivated area and estimating rice phenological parameters at a regional scale [63] [11]. High-resolution optical data (10m) is available since March 2017 from the SENTINEL-2 mission with a revisit time of five days [26]. Greater resolution images could allow for improved and detailed mapping of the heterogeneous impact of salinity in neighboring rice fields although the longer revisit time may significantly influence the number of usable acquisitions.

De Bernardis et al. (2016) developed a dynamical framework to provide real-time estimates of rice phenology stages using time-series of NDVI images [19]. Including additional sources to the NDVI, such as SAR and temperature, increased the sensitivity of the model to the phenological evolution of the rice plant [20]. Phenology is estimated each time a new satellite observation is available, hence enabling the possible detection of anomalies in real-time during the cultivation. The recent salinity intrusion event in the MKD and collected data for this research could serve as an alternative study area for future evaluations of the developed framework.

II

Social Research Report

6
Stakeholder Analysis

Stakeholders are mapped out to get insight into the affected and responsible actors concerning salinity intrusion and irrigation water management (section 6.2). This overview reveals whom to approach during fieldwork to obtain perspectives on the impact of salinity intrusion on Soc Trang province. A brief description of the background of agricultural management is provided first, as this is essential to understand the current involvement of government in Vietnamese farming (section 6.1).

6.1. Agriculture Management

Agricultural production has been the backbone of Vietnam's post-war development strategy [37]. The *Doi Moi* (Renovation) policy reforms implemented in 1986 effectively ended the system of resource allocation through central planning and have had an extensive impact on the institutional framework governing agriculture, both at the macroeconomic and microeconomic levels [28]. These reforms are the major driving force accounting for Vietnam's exceptional economic performance in the past two decades [15]. Farmers intensified rice production, diversified into new crops and improved the quality of the food they produced. By stimulating agricultural and overall economic growth, the reforms helped reduce rural poverty, hunger, and malnutrition [83].

Even though Vietnam's agricultural sector is no longer centrally planned and the household is now the primary stakeholder after the *Doi Moi* reforms [15], government involvement in rice production is high. Farmers' activities are closely monitored and supported by the commune, the local government body, where farmers report on their rice production on a weekly basis. The national government outlines Vietnam's agricultural objectives in a five-year socio-economic development plan. In every province, the plans are detailed to suit the farmers and area. In Soc Trang province, the farmer is free to decide what crop he/she wants to grow and when. The provincial Department of Agriculture and Rural Development (DARD) encourages farmers to grow certain crops or farming systems by model [17].The Vietnamese farmer reports damages and (lowered) yields to the commune, which aggregates yields and damages of rice cultivated areas and transfers this information to higher administrative levels.

6.2. Stakeholder Analysis

Stakeholders are individuals, groups, or organizations who are directly or indirectly affected by salinity problems in the region, those with responsibilities regarding the management of the water system and collection of data, and those that conduct relevant research (Figure 6.1).

6.2.1. Directly Affected

The household is the main stakeholder in agriculture with nearly 90% of agricultural land managed by agricultural households or farms [93]. Dung et al.(2017) examined the financial capacity of rice farming households in the MKD. The mean annual household income was VND 135 million (EUR 5018), and on-farm activities contributed 85% to the total household income. Household savings account for approximately 27% of the total income [24]. When salinity affects rice crops after sowing, farmers need to tap into their financial reserves to survive as no income is generated. Farm size significantly influences household saving capacity.

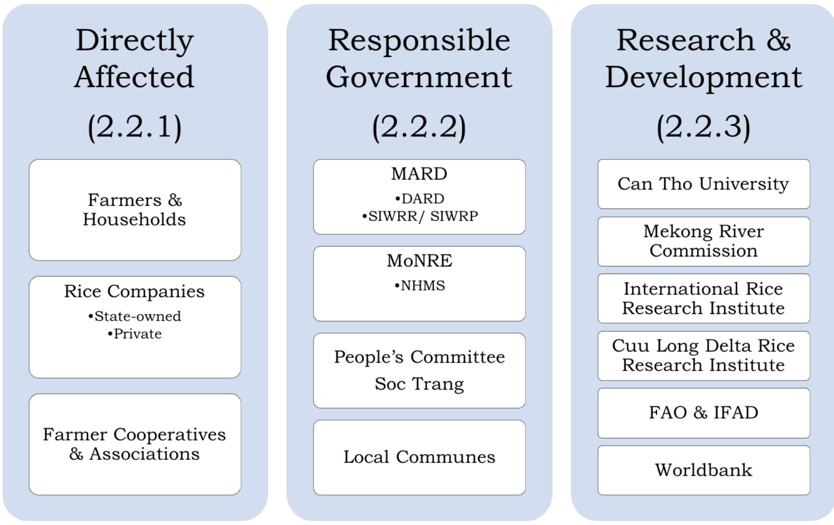

Figure 6.1: Stakeholder Overview

The combined effect of low income and low saving capacity will likely increase the challenge of managing long-standing debt among households with small farm sizes [24].

Increased competition in farming is driving market changes, and commercial farmers have emerged with 12 times the national average farm size (0.5 ha) and increased access to more credit and other resources. Many middle and lower-income farmers will find difficulties to keep up in the coming decade [28]. Farmer cooperatives have the potential to play an important role in providing services to farmers and form business-like ventures [24] [28]. Social commentators call for the need for independent associations to protect farmer's rights and provide advice for selling their products [60].

The *Doi Moi* reforms have enabled the emergence of private sector enterprises in agriculture. While state enterprises continue to dominate the export of rice, private sector firms are crucial in distributing, processing, packaging and transporting of agricultural products [15]. Recently, the Vietnamese government announced a list of 406 state-owned enterprises (SOE) to be privatized in the 2017-2020 period [39]. According to Vietnamese news sources, the government is considering divesting from SOEs in the agriculture and forestry sector [88][41] which create roles for new stakeholders in the rice market.

6.2.2. Responsible Government Institutions

The responsibility for (fresh) water resources management is divided among different governmental agencies, coordination by two ministries at the national level, the Ministry of Agriculture and Rural Development (MARD) and the Ministry of Natural Resources and Environment (MoNRE). For some responsibilities, this results in overlaps and conflicts which has led to a situation of non-responsibility [92]. In *The Vietnamese Hydrocracy and the Mekong Delta* (2014), Benedikter argues that Vietnamese water management suffers from a complex organizational-bureaucratic structure. This complexity developed through coordinating the operation of water infrastructure between state-agencies and semi-private utility companies since the *Doi Moi* reforms [3]. The following list gives an overview of the water and irrigation management responsibilities of Vietnamese government institutions.

- Ministry of Agriculture and Rural Development (MARD).
  Responsible for rural development and the governance, promotion and nurturing of agriculture and the agriculture industry. High responsibility for water resource planning and management. Surveys, designs, approves and supervises primary flood control works, such as floodgates, drainage canals or flood dikes.
  - Provincial Department of Agriculture and Rural Development (DARD)
    Manages and exploit flood control works.
    - ◇ The Provincial Division of Water Resources Management. Responsible for water management and water control work, which after approval, are built and managed with supervision

of DARD. Official agency responsible for saline intrusion monitoring and local salinity construction projects.

- The Southern Institute for Water Resources Research (SIWRR)
  Scientific governmental institute working in the field of water and environment in Southern Vietnam. The main focus is water quality, salinization and acidification of soils and water, hydrodynamic and hydraulic studies on floods, erosion and irrigation systems.
- The Southern Institute for Water Resources Planning (SIWRP)
  Research institute on water management issues in the MKD.

- Local governments at district and commune level
  Local irrigation management companies maintain flood control works.

- Province People's Committee Soc Trang
  Acts as the executive arm of the provincial government and subordinate to the central government of Vietnam. Responsible for formulating and implementing policy.

- Ministry of Natural Resources and Environment (MONRE)
  Responsible for management of land, water resources, mineral resources, the environment, hydro-meteorology, climate change; surveying and mapping; management of the islands and the sea.

  - National Hydro-meteorological Office (NHMS)
    Managing and exploiting the national hydro-meteorological station networks, carrying out observations on air and water environment to serve disaster prevention and preparedness and socio-economic development.

    - Provincial Hydro-meteorological Stations (PHMS)
      Official agencies responsible for saline intrusion monitoring. Together with DARD, they principally report to the Provincial People's Committee.

6.2.3. Research and Project Development

Since salinity intrusion is a pressing issue in the MKD, a series of local and international institutes are involved in researching the phenomenon, its impact, and possible mitigation strategies. Can Tho University facilitated this research.

- Can Tho University (CTU)
  Functions as a scientific hub in the MKD. The associated institute of the College of Technology educates students in the field of environmental and water technology.

- Mekong River Commission (MRC)
  The intergovernmental organization responsible for cooperation in the sustainable management of the Mekong Basin. Has data on flow measurements and forecasts of the upstream Mekong River

- International Rice Research Institute (IRRI)
  Knowledge institute. Develops salt-resistant rice varieties. Research about irrigation management for farmers in response to salinity of water.

- Cuu Long Delta Rice Research Institute (CLRRI)
  Situated in Can Tho. Governmental institution dedicated to agricultural research. Most rice varieties in the MKD are bred by CLRRI.

- Food Agriculture Organization (FAO), International Fund for Agriculture Development (IFAD)
  Funding Adaptation Mekong Delta Project. Includes the set-up of automated salinity network in the province of Ben Tre and Tra Vinh.

- Worldbank
  Funding Mekong Integrated Water Resources Management Project.

7
Methodology

To gather local perspectives on coping with the impact of salinity, the fieldwork team interviewed farmers and government institutions. Local government highly interacts and supports individual farmers within commune boundaries. The provincial government (DARD) details national agriculture goals to suit the different districts and influences local planning. Because of the role of government in rice production (section 6.1), interviews at the farmer, commune, and provincial level are conducted in the MKD during a period of two months from March through April at the peak of the dry season in 2017. Twelve communes are visited in Soc Trang province during ten fieldwork days, organized in six different trips from Can Tho. These communes are selected on the basis of expected land cover differences and applied farming systems. Expected is that communes with closer proximity to the coast experience more salinity problems. At the same time, farmers might also be more adapted to cope with the problems, lowering the impact of last year's salinity intrusion event.

Once permitted to conduct fieldwork (section 7.1), information is gathered through interviews with commune officials (section 7.2) and surveys (section 7.3.1) and adjusted Q-sort interviews (section 7.3.2) with affected farmers.

7.1. Preparation

Before carrying out fieldwork in the province of Soc Trang, officially approved documents are required to proceed. A detailed fieldwork plan with information on data collection for specific locations on planned days was prepared in advance and submitted for approval at different institutions. The university evaluates the plan first and sends it to the DARD of Soc Trang. The DARD is required to send a letter to the People's Committee of Soc Trang Province to ask for a fieldwork permit. Once permission was obtained after one month, a first trip to the province of Soc Trang could be organized. Because of the lengthy and strict procedure, it was not possible to deviate from the submitted fieldwork plan. Thus, there was little room for improvisation during fieldwork days or the ability to act on newly acquired information through interviews. The communes that had been suggested to visit at first ended up as the final locations.

Besides arranging paperwork, a fieldwork team was assembled with three (post-) graduate students from the land resources department of the College of Environment and Natural Resources at Can Tho University (CTU). These students would assist in survey taking and translating responses from government officials and farmers. A representative from the local Plant Protection Department in Soc Trang completed the fieldwork team. He pre-arranged all meetings at local communes, took care of official paperwork and organized transportation.

7.2. Government Interviews

Two interviews with the DARD of Soc Trang were conducted at the start and end of the fieldwork period. The vice director of DARD, the vice director of the Aquaculture sub-department and an agriculture expert of DARD joined these two hour long meetings. Communication was in English. The author met representatives from the planning sub-department of Soc Trang DARD at a conference in Can Tho (*Subsidence in the Mekong Delta: Challenges and Future opportunities*) on March 20th, 2017. This encounter, facilitated by a local development advisor of Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), led to the arranged meetings with DARD which took place in Soc Trang City.

At the start of each fieldwork day, a prearranged meeting with the head of the local commune took place. Given the right official documents and approved paperwork were provided, communes would receive the fieldwork team for an hour discussion. Notes were written down by the Vietnamese fieldwork team member and later translated to English.

Discussions with the DARD (provincial level) and local government officials (commune level) provided insights into the questions in table 7.1. Documentation on affected rice areas in Soc Trang Province was handed over in those meetings.

Government questions
1. What are reasons for salinity intrusion? Why was the impact big last year?
2. How are farmers coping with last year's event?
3. What is the future of agricultural planning in this region/commune/plot?

Table 7.1: Questions for government officials

7.3. Farmer Interviews

Two types of interviews were organized; surveys (section 7.3.1) and adjusted Q-sort interviews (section 7.3.2) (Figure 7.1). Surveys serve to collect background information from farmers, while adjusted Q-sort interviews are used to gather perspectives from farmers on different topics. Thirty farmer surveys were completed and took on average 15 minutes to complete. Of those 30 farmers, 15 in-depth interviews were realized, lasting 45 minutes.

Figure 7.1: Conducting farmer surveys (*left*) and adjusted Q-sort interviews (*right*)

7.3.1. Surveys

Thirty farmer surveys across Soc Trang province were completed through which background information about rice growing schedules, yields, income and salinity impact was obtained. Several staff members and students from the College of Environment and Natural Resources at Can Tho University (CTU) helped structure and translate the survey into Vietnamese.

Farmers were selected by commune officials who would be present at the time of the interview session. Based on reported salinity damages and availability, selected farmers would be visited. Twenty rice, eight aquaculture and two vegetable farmers were interviewed at their homes. Coordinates of visited farmers' fields were taken. Different Vietnamese students (CTU), members of the fieldwork team, would conduct the survey questions. Completing one survey lasted 15 minutes. Notes were taken by the Vietnamese fieldwork team member and later translated into English. Results from conducted surveys are mainly used in Part I of this research. In addition to interpreting remote sensing analysis with quantitative data, the information served to develop a thorough understanding of the problem and context of the farmer household. Survey results are not explicitly discussed, though findings are incorporated throughout this research.

7.3.2. Adjusted Q-sort

When visiting affected rice farmers around the province, additional in-depth interviews with 15 farmers were realized. To obtain perspectives from farmers, a Q-methodological approach was used because this technique allows for exploration of viewpoints and statistical analysis using a small sample size [58]. Fifteen farmers in different communes across the province ranked 44 statements from agree to disagree. These statements are included in Chapter 8, table 8.2. Using statements as compared to questions in in-depth interviews can help respondents order their thoughts and express themselves in more detail [57]. The subsequent ordering of the statements in a fixed distribution from agree to disagree forces the respondents to evaluate their perceived importance of statements.

The set of statements, called the discourse, were drawn up carefully in advance of the fieldwork. These statements addressed a central question, formulated as; "what is your perspective on the current and future impact of salinity intrusion on your (rice) farming activities?". Through literature study and discussions with experts, a series of subtopics to structure the discourse was generated (table 7.2). Related questions were drawn up to aid the development of statements (table 7.3). Next, the broad range of perspectives (statements) was evaluated by four students from the college of environment and natural resources at Can Tho University. These students were selected because they either had experience with the topic of salinity intrusion, interviewing farmers in the field or came from farming families. The students were asked to pay attention to relevance, repetitiveness, and comprehension of the statements. The sessions led to the selection of 44 statements, which were thereupon randomly numbered, translated to the local dialect of the MKD and printed on cards for Q-sorting.

During sessions at the farmer's house, statements were read out loud by a Vietnamese fieldwork team member and the farmer was asked to reflect on the statement. Did he/she agree, disagree or remain neutral with the subjective statement? In a regular Q-sorting session, the farmer would then, in a second round, make a final sorting of the statements in a fixed flat distribution, usually spanning nine columns or more [90]. Due to the slow reading process with often illiterate farmers, prevailing high temperatures and constraints to other type of data, this final sorting element was omitted in the end. Instead, an agreement ranking of statements was visually built up on the table in front of the farmer. When all the statements had been placed in one of the three columns; agree, neutral and disagree, the farmer was asked to select four statements he found most important and explain his/her reasoning. Notes were taken by the interviewer and later translated into English.

During the session, the opportunity to ask for elaboration on placements of statements remained limited because of time constraints and the fieldwork team's translation abilities. Therefore, the selection process was added to mimic a quick post-sorting interview, as this element can provide in-depth insight into the beliefs and values underlying the Q-sorts [33]. With an adjusted version of the Q-sorting technique, an in-depth interview lasted 45 minutes for one farmer.

Topics
1. Cause and severity of salinity intrusion
2. Government irrigation management
3. Reflection on rice production
4. Adaptation by changing activities
5. Mitigating salinity problems
6. Aquaculture production development
7. Salinity warning effectiveness

Table 7.2: Q-sort Topics

Related questions for topics in table 7.2
1. What factors caused the salinity intrusion to be severe? Will it become worse?
2. Is the irrigation system well managed in regards of the salinity problems?
3. What is your perspective on current rice production, income and exposed (future) risk?
4. Do you want to switch farming activities? Why & How? Are you free to do so?
5. How do think you can mitigate the effects of salinity intrusion?
6. What do you think about the increase in aquaculture production?
7. What do you think about a salinity warning?

Table 7.3: Questions for Rice Farmers

8

Results

Discussion points from interviews at the provincial, communal and farmer level are presented in this section. The information provided in section 8.1 is summarized from an interview with representatives from DARD Soc Trang. The responses of (12 different, Figure 8.1) commune leaders are ordered by districts in section 8.2. Tables on affected rice areas can be found in Appendix F). Section 8.3 shows farmers' valuation on the discourse of statements.

8.1. Province

The salt intrusion event last year came as a surprise. The lack of rainfall resulted in water scarcity. Initially, the high level of salinity was not known. The sluice gates were closed but were so for a long time. The salt intrusion length was much longer than previous years and reached all the way to Ke Sach district. At this height, there are no sluice gates. There was also salt intrusion from the West ocean to Soc Trang province, arriving from Bac Lieu province. Lots of farmers lost their crops; the aggregated numbers are provided in the table F.2. Besides the damages that occurred, DARD also sees the benefits of salt intrusion and the opportunity to change rice crops to aquaculture. When the rice area decreases, aquaculture will increase in the province.

DARD is concerned about climate change. The weather is unpredictable these days. The farmer has a long-time experience with the weather patterns and knows how to interpret it, and decides when and how to grow rice. Nowadays farmers are confused as the rain patterns are different from the past. As a response to last year's salt intrusion, the government advises planting the rice later this year. However, this year there is no salt intrusion, and the advice does not match the unpredictable weather.

As a response to salinity intrusion, DARD has the policy to try to save existing rice areas by building a dike along the affected area and investing in the irrigation system. Salt intrusion is very high in some areas near the ocean. These areas cannot be saved, and the DARD helps farmers to transfer to other farming systems. Technical methods for rice areas include changing the time for planting rice, encouraging salt-tolerant rice variety, encouraging the growth of other salt-resistant crops (vegetables, coconut), and combining rice and growing shrimp in the salinity affected season. For aquaculture farming, DARD focusses on the seeds (larvae) that are suitable for this area and provides training to increase knowledge on how to grow shrimp successfully.

DARD does not force farmers to farm a certain way. The farmer is free to decide what and when he wants to grow his crop. The government does encourage farmers to grow certain crops or farming systems by model. For example, in Long Phu district, they are running pilots with watermelon and corn. The local government invests in some farmers to encourage farmers around of the working model. DARD also encourages farmers to work together and provides technical training.

The DARD reports on salinity damages in the region through a system of local plant protection stations. There is a good connection with the farmer and the local government. The farmer comes to ask the commune for help and reports once a week to the local government on the status of his/her crops. The head of the village will report damages to the commune. All the information combined will arrive at DARD.

8.2. Commune

Tran De The visited communes of Lieu Tu and Trung Binh in Tran De district did not experience a lot of salinity problems. In Thanh Thoi Thuan Commune, 300 ha out of 2250 ha of rice fields were affected. The cause

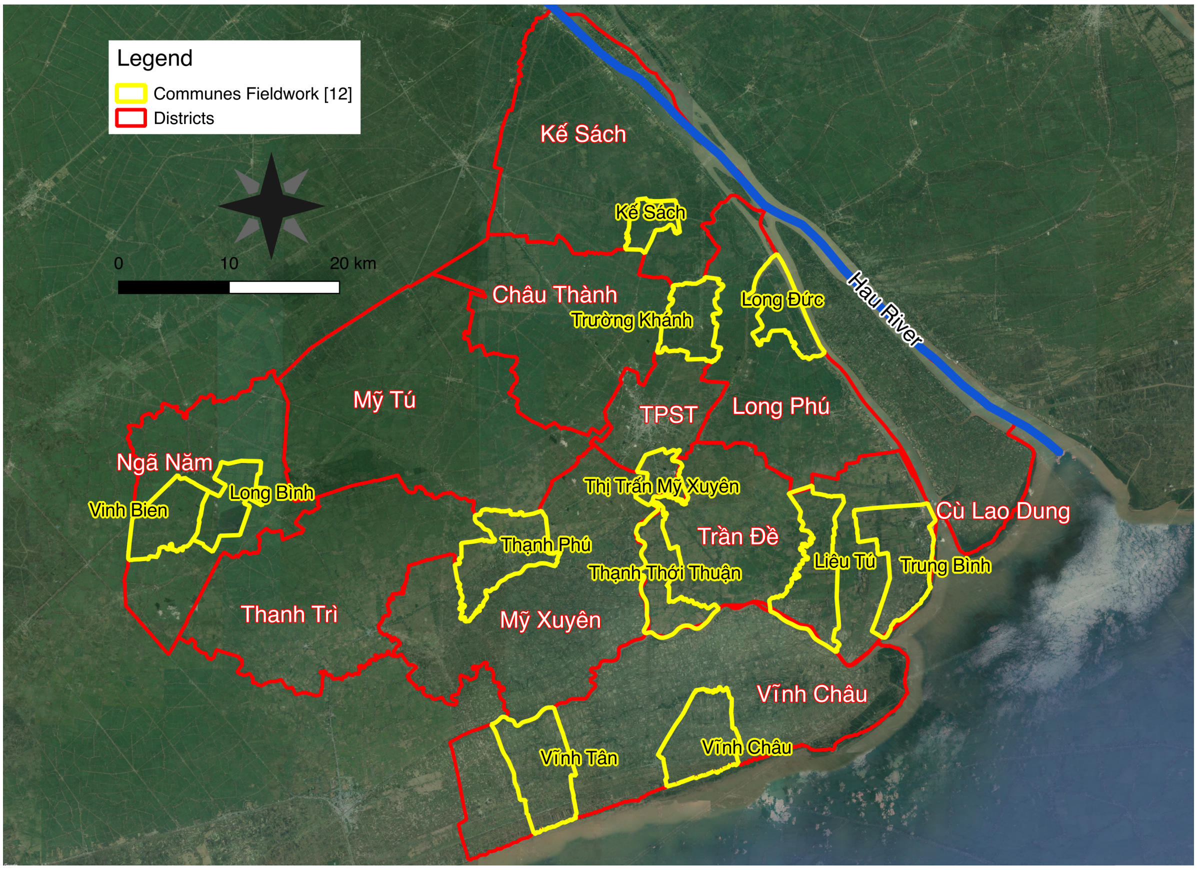

Figure 8.1: Visited communes during fieldwork

of the intrusion was attributed to the location of the commune, which lies at the end of the dike system. Also, a broken sluice gate needed to be fixed. Besides the affected hectares, the commune experienced very high yields due to late cropping, favorable climate, and enough fresh water. The future status of the commune depends on climate change. Adaptable plans include irrigation solutions, storing water, fixing sluice gates and repairing the main water channel. Furthermore, the commune places an increasing focus on growing livestock. Farmers went from holding 200 cows in 2015 to 700 cows in 2017. The commune encourages farmers to grow cattle.

Long Phu Part of Long Phu district is outside the 'Tran De' water management system, where more rice-shrimp rotational farms can be found. In Long Duc commune, agriculture was affected by salinity during four months and 600 ha out of 1329 ha of rice was lost. Drought and leakage of saline water through the system caused the severity of the intrusion, not the management of the sluice gates. This season only 196 ha are planted during the Spring-Summer crop. The government wants to adapt to avoid last years' problems and they encourage rice farmers to change to vegetable production. Some farmers still plant rice because they have traditional technologies. In the future, a new policy might be necessary to switch from 3x Rice to a 2x Rice system or focus on growing another type of crops like chili, watermelon, vegetables. The commune is currently running a corn pilot of 25 ha that can return high values of VND 3 million/ ha. However, farmers do not like to change as they are familiar with the 3x rice farming system. Local members of the commune go to the farmer to advise and teach. There is no monetary support for farmers to switch farming systems.

In Truong Khanh commune, 731 ha of rice were affected by salinity. Officials state that the water system is well managed and that climate change, weather changes, and drought caused the salinity intrusion. The farmers in the commune are familiar with planting rice. They usually plant rice 3x during the year. his year, however, 90% of the farmers did not plant rice during the 3rd season. Some planted vegetables on small plots (1ha) instead, others went to find temporary work in other places. Some farmers plant lotus, but seldom has high value b/c production value fluctuates heavily with the weather. Because the water in the commune is of light salinity, it is not suitable for a rice-shrimp combination which needs higher salinity. Suitable policies for the future include changing to a model with rice and upland crop (coconut, orange).

Ke Sach The commune in Ke Sach district attributed the salinity event due to unusual weather. Rice growth was affected in the booting and flowering stage. A total of 6 villages with 529 families holding 344.92 ha of rice, were affected by the salinity event. The total rice area is 792 ha. The commune has a large orchard area of 427,22 ha (Longan, rambutan, durian, star apple). Orchards are not directly affected by salinity such as the rice crops that fails, but salinity is taken up by the trees and effects are visible six months later. At the time of visit, the commune was listing the orchard farmers that had been affected. Commune leaders believe the salinity was a one-time event, so there is no need for current action. If the salinity becomes worse, changing the rice variety and converting to vegetable or corn will be adopted in future agricultural planning.

My Xuyen The government officials of TT M Xuyên commune attributed the salinity intrusion problems to the high tide and the incomplete dike system. Salt water could come into the field in the ripening stage. Government is now taking action on repairing the dike system. 72 ha out of a total of 760 ha rice was affected, consisting of 2x rice areas (460 ha) and rice-shrimp rotational areas (300 ha). The latter farmer cannot change the timing of the crop because he depends on the rainfall. The commune is thinking about planting vegetables as a mitigation strategy.

In Thanh Phu commune in M Xuyên district, the salinity event disturbed 256 families. 259 ha of total 1618 ha of rice area were affected due to a lack of water from upstream in the dry season and the high level of the sea water. The salinity was highest in January and February at the time of harvest of the Winter-Spring crop, which was lost. The government has improved the gates and dike system. Therefore, the current farming models can be maintained. Part of a structural plan includes canalizing rivers and canals to store water in dry season. When needed, the commune will change to grow rice varieties that can adapt to salinity (2-3%). Some weak rice areas can change to grow grass for cows.

Nga Nam In Nga Nam district, the salinity intrusion problems are felt in the visited communes of Long Binh and Vinh Bien. The problems are due to the canal system and flow of saline water which arrived from 2 directions. From the coastal Bac Lieu province along the Phung Hiep Highway canal ocean water flows to Nga Nam district. From Kien Giang province, located north-west of Soc Trang province, saline water flows from the West Sea to the west of Nga Nam town. Nga Nam collaborates with the units in Bac Lieu and salinity events will be promptly notified and dealt with to ensure that only diluted salt water enters the rice fields. Because of this communication between provinces, the rice farming is not affected that much. In Vinh Bien commune, the salinity affected 700 ha out of 2800 ha of rice. For the inefficient rice growing areas, it is possible to gradually change to fresh aquaculture and fruit products. In Long Binh, only 10 ha of 1920 ha of rice were affected.

Vin Chau The communes in Vin Chau coastal district are adapted to salinity affects. The communes are the leading producers of aquaculture in the province of Soc Trang. Many vegetables, such as onions, are also produced. In Vinh Tan commune, Last year's drought lowered the groundwater table significantly. There was less water available for daily activities and irrigation which affected some vegetable production. Considering climate change processes, the commune is worried about the ground water level because the farmer cannot pump to use it. The commune will keep the current agricultural model of vegetables and shrimp. Shrimp is the main income of the population. Upland crop is cultivated on higher elevation areas in the commune.

8.3. Farmer

In table 8.2, farmer's valuations on statements are quantitatively presented. Figure 8.2 presents selected statements with the highest (dis)agreement rankings. The results are discussed in section 9.2.

"Obtaining high rice yields is becoming more difficult for me over the past years because of salinity problems" (15 agree)

"I will resettle if the dry season conditions get worse for growing rice in my location" (14 disagree)

"Planting more salt-tolerant rice varieties is a good way to cope with salinity problems" (15 agree)

"I am not worried about the available water and its salinity concentration in the dry season in the future" (13 disagree)

"If salinity levels will become higher in the future, I will have to stop growing rice" (14 agree)

"I want to grow rice 3x/ year; I do not like a policy to change to cropping rice 2x/year" (12 disagree)

Figure 8.2: Selected statements and scores

Topic 1	*Cause and severity of salinity intrusion*			
Central Question	**Q: What factors caused the salinity intrusion to be severe? Will it become worse?**	**Disagree**	**Neutral**	**Agree**
Statements	(1) Salinity intrusion is not caused by leakage of saline water through the water management system	8	1	4
	(2) Poor management of water infrastructure (sluice gates) is causing salinity intrusion problems	5	5	5
	(3) More salinity intrusion in the dry season is not caused by changing weather patterns	11	1	3
	(4) Expansion of agricultural areas (more farmers who need water) is causing water scarcity in the district	8	1	6
	(5) Salinity intrusion is not becoming more severe	12	0	3
	(6) The severity of salinity intrusion fluctuates every year; it is impossible to state whether the situation is becoming worse	3	1	11
Topic 2	*Government management of agriculture/irrigation*			
Central Question	**Q: Is the irrigation system well managed in regards of the salinity problems?**	**Disagree**	**Neutral**	**Agree**
Statements	(7) Decisions to manage the salinity concentration of the water (opening/closing sluice gates) are not made in consultation with me and other farmers.	7	3	6
	(8) The government does a good job zoning rice and aquaculture production to prevent salinity problems	2	2	11
	(9) The government listens well to the farmers' problems and creates policies based on our experience	0	2	13
Topic 3	*Reflection on rice production*			
Central Question	**Q: What is your perspective on current rice production, generating income and exposed (future) risk?**	**Disagree**	**Neutral**	**Agree**
Statements	(10) I save money because there is a high risk the harvest in the dry season failes	5	0	10
	(11) With my current production, I make enough money to sustain my family.	4	1	10
	(12) When my harvest fails in the dry season, I become indebted.	3	0	12
	(13) Planting rice will give me subsidies, other crops do not	3	4	8
	(14) I obtain the highest rice yield in the dry season; it is the most productive season	0	2	13
	(15) I will have to change my farming practices to sustain my family in the future	4	0	11
	(16) Every dry season, I take a risk to irrigate my rice crop with the surface water	2	0	13
	(17) Instead of planting a lower yielding (salt-tolerant) rice-variety, I bet on rainfall in the dry season to obtain the highest possible rice yield.	11	0	4
	(18) Obtaining high rice yields is becoming more difficult for me over the past years because of salinity problems	0	0	15
	(19) Growing rice nowadays not a risky activity	5	2	8
	(20) I am not worried about the available water and its salinity concentration in the dry season in the future	13	0	2
	(21) If salinity levels will become higher in the future, I will have to stop growing rice	1	0	14
Topic 4	*Adaptation by changing activities*			
Central Question	**Q: Do you want to switch farming activities? Why & How? Are you free to do so?**	**Disagree**	**Neutral**	**Agree**
Statements	(22) I want to (switch to) produce shrimp because it gives me a higher value	10	1	4
	(23) A mixed farming system with shrimp and rice is a good farming option for me to deal with salinity problems	9	2	4
	(24) I want to change cropping actvities to make more money, but I do not know how to do it.	3	3	9
	(25) I need to change my cropping activities next season, because my harvest failed last year.	9	0	6
	(26) If the government supports it, I would change my current practice to grow a different product	3	1	11
	(27) I want to grow rice 3x/ year; I do not like a policy to change to cropping rice 2x/year	12	0	3
	(28) In my commune/district, I am not free to decide what I want to grow.	11	1	3
	(29) I calculate which type of crops or rice-varieties I should grow, according to market demand and location suitability	1	1	13

Table 8.1: Discourse Farmer Interviews

Topic 5	*Mitigating salinity problems*			
Central Question	**Q: How do think you can mitigate the effects of salinity intrusion?**	**Disagree**	**Neutral**	**Agree**
Statements	(30) Shifting rice crop seasons is not a good way to cope with salinity problems	11	2	1
	(31) Planting more salt-tolerant rice varieties is a good way to cope with salinity problems	0	0	15
	(32) Switching to grow other type of crops is not a good way to cope with salinity problems	0	3	12
	(33) Application of agro-chemicals will help to improve rice yield in saline conditions	5	3	7
	(34) Better available farming techniques will not increase my rice productivity (yields) further	12	0	3
	(35) I will resettle if the dry season conditions get worse for growing rice in my location	14	1	0
Topic 6	*Development of aquaculture production*			
Central Question	**Q: What do you think about the increase in aquaculture production?**	**Disagree**	**Neutral**	**Agree**
Statements	(36) More aquaculture production causes more salinity in the surface water which affects other (rice)farmers	3	2	10
	(37) I think more aquaculture production is good for Soc Trang because it has suitable conditions	2	5	8
	(38) Farmers in Soc Trang province should focus on producing rice, not other crops or aquaculture	8	2	5
	(39) Ricefarmers negatively effect the shrimp producers because of pesticides in the irrigation water	1	4	10
	(40) Growing aquaculture is a risky activity	1	4	10
Topic 7	*Salinity warning effectiveness*			
Central Question	**Q: What do you think about a salinity warning?**	**Disagree**	**Neutral**	**Agree**
Statements	(41) We, farmers, do not receive adequate salinity warning on time from the government	12	1	2
	(42) When I receive a salinity warning, I can make decisions that would save my crops or reduce the damages	2	1	12
	(43) After the rice is already planted, a salinity warning would not be helpful anymore; there is nothing I can do to minimize damages.	3	2	10
	(44) When I taste the water I can guess the salinity concentration, and estimate good whether it is too high	6	1	8

Table 8.2: Discourse Farmer Interviews con'd

9

Discussion

A concluding summary of discussions on causes of the salinity intrusion, coping mechanisms and future of agricultural planning with government officials is provided, followed by conclusions on farmer perspectives. A brief reflection on the reliability of the results is included as well as a general reflection on the methodology.

9.1. Government Perspective

The causes of the severe salinity intrusion mentioned by interviewed officials are drought, high tide, broken sluices gates, leakage of saline water through the system but never the operation of the sluice gates. Some commune leaders in less affected areas believe the salinity was a one-time event, so there is no need for current action. In the majority of locations, however, an urgency to act on the salinity problems exists. Nowadays, farmers are unable to interpret the weather patterns as before, as it became unpredictable. As a response to last year's salt intrusion, the government has stopped encouraging farmers to grow rice in the Spring-Summer season or advises to plant the rice later. In Truong Khanh Commune, 90% of farmers did not plant rice in the dry season of 2017. Some planted vegetables on small plots instead Others went to find temporary work in other places. Since farmers have traditional technologies and do not know how to grow another crop or where to find other sources of income, some still grow rice.

As a response to salinity intrusion, local governments try to save existing rice areas by building dikes along the affected area and investing in the irrigation system. Some communes have improved the gates and dike system and the current farming models can, therefore, be maintained. In some areas, salt-intrusion is too high and the rice area cannot be saved. Technical methods of adaptable plans mentioned by government officials are; switching from triple cropping rice to double cropping rice systems, changing the time for planting rice, planting salt-tolerant rice varieties, encouraging suitable farming systems that combine rice with vegetables and/or upland crop (coconut, orange), growing livestock and combining rice and shrimp in the salinity affected season. In Long Phu district, pilots to grow melon and corn are set up to encourage other farmers to switch. The provincial government (DARD) also recognizes the benefits of salt intrusion and the opportunity to change rice crops to aquaculture. To boost aquaculture farming, DARD provides training to increase knowledge on how to grow shrimp successfully.

In the visited coastal communes of Vin Chau, last year's drought lowered the groundwater table significantly. Less water was available for daily activities and irrigation which affected vegetable production. Drinking water was transported from other groundwater sources as the wells in Vinh Tan commune were depleted. The commune is worried about the future ground water level for the vegetable farmers as they cannot pump to use it.

9.2. Farmer Perspective

Farmer perspectives on salinity impact were evaluated posing a series of subjective statements. Fifteen farmers were then asked to reflect upon statements and rank them according to their level of agreement.

Topic 1: Cause and severity of salinity intrusion & **Topic 2**: Government management

The majority of interviewed farmers (12) expect the salinity problem to increase in the future. Perceived fluctuations in salinity concentrations over the years increase the uncertainty of that prediction (11 agree).

Changing weather patterns is therefore perceived as the dominant cause of salinity intrusion. Eight farmers think that leakage of saline water through the water management system caused salinity intrusion. Opinions on the wrongful operational management of water infrastructure as the cause of salinity intrusion are divided. The decision to operate (open/close) sluice gates are not always made in consultation with the interviewed farmers. Nevertheless, farmers respond overall positive on critical statements about government management responsibilities and activities. Eleven out of 15 farmers believe that the government does a good job zoning rice and aquaculture production to prevent salinity problems. Moreover, 13 out of 15 farmers trust that the government listens well to their problems and creates policies based on their experience.

Topic 3: Reflection on rice production

Of the 15 farmers, all agree with the statement 'Obtaining high rice yields is becoming more difficult for me over the past years because of salinity problems.' Thirteen out of 15 farmers are 'worried about the available water and its salinity concentration in the dry season in the future,' and 14 farmers acknowledge they will have to stop growing rice if conditions become worse. These results reflect the current challenging and uncertain conditions for the rice farmers in Soc Trang province. Twelve out of 15 farmers agree that every dry season they take a risk when irrigating their rice crop with the surface water. When their dry season harvest fails as a consequence, 12 farmers state they become indebted. Because of this dry season risk, 10 out of 15 of farmers save up money. Ten out of 15 rice farmers make enough money to sustain their families with their current production, but an equal percentage of farmers realize they will have to change their farming practices to sustain their families in the future.

Topic 4: Adaptation by changing activities

The majority of farmers (13) feel free to decide which crops to grow on their land. These farmers calculate which type of crops or rice varieties they should grow, according to market demand and location suitability. Nine out of 15 farmers want to change cropping activities to make more money, but do not know how to do this. If the government supports it, 11 out of 15 farmers will change their current practice to grow a different product. Nine farmers deem there is less immediate need to change cropping activities next season due to recent harvest failures. In many visited communes, double cropping rice schedules best suited the prevailing conditions. Therefore twelve farmers disagree with the statement; 'I want to grow rice 3x/ year, I do not like a policy to change to cropping rice 2x/year.'

Topic 5: Mitigating salinity problems

Fourteen out of 15 farmers state that they will never 'resettle if the dry season conditions get worse for growing rice in my location.' Even though farmers are worried about the future of their agricultural production, they would at no time consider leaving their grounds. Farmers in the MKD feel connected to the land on which their ancestors are buried. One farmer states that he is connected to his area for many years, and has built relations with other people. He also finds it difficult to change his customs of rice production as this is a longtime family tradition.

To keep growing rice in the future, farmers could plant salt-tolerant rice varieties. All 15 farmers believe this is a good way to cope with the current salinity problems. Shifting rice crop seasons is considered a good way to cope with salinity problems (11 out of 15), whereas switching to grow other types of crops is not the desired mitigation measure (12 out of 15). Farmers expect (12) that better available farming techniques in the future will increase their rice yields.

Topic 6: Development of aquaculture production

An alternative to growing rice in a saline threatened environment is to switch to brackish aquaculture production. Aquaculture is a profitable but risky business at the same time (10 out of 15 agree) as seedlings easily catch diseases. Therefore, ten rice farmers indicate they do not want to (switch to) produce shrimp even though more money could potentially be made. Furthermore, a rice shrimp rotational farming system is not considered the most favorable option to deal with salinity problems. When asked for their opinion on developments for Soc Trang province as a whole, eight rice farmers agree the province has suitable conditions and should focus more on aquaculture production. The other half concludes that the province should focus on producing rice, not other crops or aquaculture.

Topic 7: Salinity warning effectiveness

Most farmers (12 out of 15) acknowledge they receive adequate salinity warning on time from the government and they can use the information to make decisions that would save their crops or reduce damages. However, 10 out of 15 farmers acknowledge that timing of the warning is crucial. After the rice is already planted, a salinity warning would not be helpful anymore; there is nothing the farmer can do to minimize damages.

9.3. (Dis)agreements in Responses

Some results are found to be somewhat conflicting. Farmers address the need to change their cropping activities to sustain their family in the future. If salinity levels become higher, rice production is unsuccessful. Changing farming activities does apparently not include switching to grow other types of crops, as farmers do not consider this a desired mitigation measure. This result may point to the strong cultural relationship with growing rice in the MKD as well as a lack of knowledge on how to grow another type of salt-resistant crops. The statement may also have been open for different interpretations on what type of crops are considered for cultivation, which could explain the inconsistency.

9.4. Reliability of Results

Visited local communes operate independently yet the summarized section (9.1) on government perspective can be considered representative. The DARD of Soc Trang governs all districts and communes within the province and was interviewed extensively on provincial management issues. In total, 14 interviews of approximately 16 hours allowed for a profound exploration of the government perspective on the salinity problem and its impact on the province of Soc Trang. Interviewees were able to speak freely and the exploratory questions were framed objective and straightforward.

The results from the adjusted Q-sort represent a small number of interviewed farmers (15). These farmers were (carefully) selected by commune officials and their responses influenced by the presence of those officials. During some fieldwork days, police officers followed the research team around and sat in on interview sessions. On one occasion, some statements were removed from the stack by a police officer because of perceived sensitivity concerning the government. Especially responses to statements 2, 7, 8, 9, 26, 27, 28 and 41 which involve subjective opinions on government (non-)activity are expected to be highly biased in the results. Therefore, some conclusions in the farmer perspective (section 9.2) are not reliable as farmers were pre-selected and not able to speak freely on specific topics. The rest of the results still provide valuable insight into the reality of farmer's lives in the context of salinity intrusion.

9.5. Reflection on Methodology

The Q-sort methodology was selected to map out farmer perspectives. Performing a full Q-sort interview soon proved to be impractical out in the field. On-the-spot adjustments enabled improved speed of conducting the interview. Removing the essential element of the Q-sort methodology; the sorting of the statements; was unfortunately necessary. Covering all 44 statements in the interview lasted on average 45 minutes. In retrospect, an interview method with a shorter duration would be preferred, given the dry season temperatures in the MKD. Farmers were also often visited around lunch hours, at the hottest moment of the day. Therefore it was physically demanding to engage in discussions for everyone involved.

A few statements were found to be redundant or obvious for the farmer, such as 'if salinity levels will become higher in the future, I will have to stop growing rice.' Some statements were difficult to understand and took several explanation attempts to get the point across. The stack included statements which would cover the essence of problems experienced. Farmers felt acknowledged in their struggles and therefore content to share their thoughts with the fieldwork team. The results of the final adjusted Q-sort interview give insight into farmer perspectives on different topics, but drawing quantitative conclusions on perspectives is limited. Statistical analysis on statements to map out different perspectives within the group of farmers is no longer applicable because of the applied adjustment to the Q-sort methodology. The final interview methodology served an exploratory purpose.

Lots of information was gathered through interviews, surveys, and adjusted Q-sorting within ten days of fieldwork. Nonetheless, the number of responses cannot result in statistically significant conclusions. With gained knowledge on challenging aspects of organizing fieldwork in Vietnam (section 7.1) as well time management issues to collect different type of data for the remote sensing and social research study, the focus of research could be reevaluated (section 10.3).

10
Synthesis

The study is organized to cover two aims; to map the impact of salinity intrusion on rice productivity in a remote sensing study (part I) and to investigate how that impact influenced farmers' lives and perspectives in a social research (part II). Conclusions which reflect the main points from part I and part II are presented in section 10.1. The following discussion on the integration of remote sensing analysis and social research in section 10.2 includes a reflection on applications discussed in the introduction chapter; how remote sensing can support agricultural planning and improve farmer livelihoods. Last, suggestions to improve future research (section 10.3) are pointed out.

10.1. Conclusions

Part 1: Remote Sensing Analysis

Rice areas in the province are mapped by applying supervised classification and a rice peak detection algorithm on MODIS NDVI time-series. Distinct rice cropping schedules appear within district boundaries using peak detection analysis. Compared against an estimated climatology, hampered rice growth is detected for two hot-spots ('Long Phu' and 'Nga Nam') in the province of Soc Trang using satellite data and collected ground data. The delineated anomalies can be attributed to salinity problems through interpretation of ground collected information and an understanding of the local salt-intrusion mechanisms. To identify salinity-affected rice areas in other delta regions, an independent information source on salinity intrusion (ground data or model) is necessary to apply the approach set out in this study.

Reconciling affected rice areas in units of grid cells from remote sensing analysis with recorded hectares of damaged rice at district and commune level is difficult. The resolution of MODIS data could be too coarse for the scale of this provincial study. Possible inaccuracies of collected survey and obtained government data during fieldwork are non-traceable. Moreover, the NDVI saturates at high biomass and the relation between the detected maximum NDVI and lowered productivity levels is unverified. The Kalman filter used to smooth the NDVI time-series reduces the information content of the NDVI signal and may have lowered the ability to deduce information about the impact of salinity stress in rice crops.

Part 2: Social Research

The widespread salinity intrusion event in 2016 alarmed many farmers and agricultural planners in the MKD. The impact on yields and cropping cycles disturbed farmer lives. Analyzed perspectives of salinity affected farmers highlight the uncertain conditions and future for rice production in the MKD. By seeding their fields during the dry season, farmers take a high risk as they often become indebted if the rice season fails. Many realize they will have to stop growing rice and need to change their farming practices to sustain their families in the future.

Interviewed government officials and farmers are both aware of the changing climate conditions and the need to either respond through preventive or adaptive measures to avoid similar impacts of salinity intrusion in the future. Adaptive measures include decreasing rice cropping cycles, changing the time for planting rice, planting salt-tolerant rice varieties, changing farming systems to combine growing rice with other (more salt-resistant) crops, aquaculture or livestock. Mitigation strategies will never include resettling as farmers are attached to their ancestral lands. For the provincial government, salinity provides an opportunity to change rice crops to aquaculture. Rice farmers seem hesitant to switch to brackish aquaculture as production incorporates a high risk of failure.

Among farmers there exist an overall high trust in government execution of responsibilities for irrigation management. These conclusions may have been biased by the presence of government officials during interviews. The attitude of local governments is adaptable, but farmers need to be supported more and receive training to cope with worsening conditions in the dry season or to grow other types of crops or aquaculture. Salinity conditions are likely to increase in the future, and therefore, adjusting rice production will be inevitable in Soc Trang.

10.2. Reflection on Integration

The initially broad scope of this study resulted in the final presentation of two research parts. Findings in the social research (part II) complement the remote sensing analysis (part I). Soft information collected throughout the province of Soc Trang helps to understand whether deviations from average rice growth curves (anomalies) are related to salinity. The advantage of remote sensing lies in its objective measure of the scale, duration and timing of anomalies. The advantage of ground data is gaining an understanding of what caused the rice growth anomaly and the practical impact of it.

Satellite data are considered hard data which are objective and quantitative and ground data collected from communes and farmers are considered soft data. There are fundamental differences in the way these data types are collected and presented (using different units). Reconciling processed hard data and soft data collected during fieldwork to draw quantitative conclusions is difficult in this study, which is partly due to our limited external access to detailed government data on rice production and yields. The potential for the intensely documented agricultural context of Vietnam to validate remote sensing analysis has therefore not yet been fully explored.

Responses from a limited number of rice farmers are collected through surveys, which can not be used to draw statistically significant conclusions. Extrapolating information about rice growing schedules, yields, income and salinity impacts from individual rice fields to represent a commune or district scale value does therefore not apply. The results of the final adjusted Q-sort interview give insight into farmer perspectives on a variety of topics. Drawing quantitative conclusions on perspectives remains limited because of necessary adjustments in the methodology (section 9.5). Nonetheless, conducting farmer surveys and adjusted Q-sort interviews was essential to gain physical insight of what happened on the ground and what caused the problem. Soft information was used to interpret remote sensing results qualitatively, as presented in this research.

Integrating remote sensing analysis and social research in this study includes above-mentioned challenges. Typical fieldwork for remote sensing analysis consists off collecting land use classification points. Valuable opportunities to improve remote sensing research with 'social' data arise when conducting fieldwork. If well organized and granted full accessibility, quantitative data can be collected through surveys and interviews with individuals which can be used for validation. Interviews with farmers and government officials provide contextual learning opportunities to better direct, develop and interpret remote sensing analysis and results. There are underlying physical mechanisms and human decisions which influence observed data and derived rice productivity information, which can never be detected with a satellite unless ground data can serve to interpret.

Remote sensing studies are often analyzed with aggregate data from international financial and agriculture development institutions. This research shows how using moderate resolution MODIS satellite imagery, salinity impact on rice productivity on district scale can be mapped using ground data collected at a local scale. From an international research perspective though, setting up fieldwork in Vietnam is not easy due to the bureaucratic process to obtain permission, as described in section 7.1. With remote sensing observations, dealing with institutional complexity can be avoided. Once trends in rice growth curves are observed and a climatology established, rice growth stages can be estimated. For an area with known salinity issues, rice growth problems can be detected.

10.2.1. Support Agriculture Planning

Remote sensing has potential to support agricultural planning in the MKD. Government institutions at all administrative levels invest to collect data on (damaged) rice production. Money, time and efforts can be differently spent when accurate monitoring of rice crop growth using satellite data is possible. Mapping affected rice areas with MODIS data and analysis techniques as covered in this research cannot yet function as an operational tool for DARD. The accuracy levels of the results are not sufficiently tested to suit the provincial level, and to direct adaptive practice in critical rice areas. At this time, DARD could benefit from setting up a GIS information database, to process and map all aggregate data on affected rice areas throughout the province. With infrastructure and human capacity in place, improved available remote sensing applications to support agricultural planning could be gradually integrated into future policy-making. Also, large rice export companies, such as Loc Troi Group, benefit from spatial information on rice productivity to adjust or diversify their business.

10.2.2. Salinity Warning for Farmers

Gathering perspectives of farmers and government officials on the salinity problems in the region was used to explore whether remote sensing analysis could improve farmer livelihoods. There exists little benefit for the individual farmer in the field to detect salinity indirectly through observing rice crops with satellite data. However, based on satellite observations, rice crop growth stages can be detected. If this information is coupled with crop simulation models or simply interpreted with typical rice growing schedules, it is possible to predict when sensitive rice growth stages occur. When a network of ground salinity measurements is added, salinity warning messages could be sent to individual farmers with vulnerable rice fields.

In many of the visited communes, salinity warning systems are already in place. According to the interviewed farmers, the government provides an adequate warning on time (section 8.3). There exists reason to call this result into question given the many hectares of damaged rice in the province. Only a salinity warning that predicts concentrations weeks in advance is of use since nothing can be done to minimize damages once the rice has been planted. An early warning system for salinity at a system level (MKD) works well, but local salinity monitoring is complex as concentrations are governed by the integration of human-operated sluice systems with the natural tide system. Predicting salinity concentrations at the local scale with a hydraulic model is impossible because of the multitude of influential factors [32].

10.3. Suggestions

To cover both research aims (section 1.1), data collection was organized to collect a broad range of data types from coordinates of different land cover classes, to data on the productivity of rice fields, as well as farmer's opinions on hampered rice productivity. The study has benefited from the integration of remote sensing and social analysis, through which a rich understanding of the problem to interpret remote sensing analysis was acquired. The author recognizes that opportunities for quality improvement exist in both parts of the research. The approach and methodology would be revised in both research parts if the focus of the entire research would be on one or the other.

To improve the remote sensing results, more data on rice yields and salinity impact at several other locations could be collected to cover the entire province. As suggested in the section 10.1, the impact analysis using moderate resolution MODIS satellite data could better fit a Mekong Delta-wide study. Future fieldwork can be organized to collect data in other vulnerable rice provinces around the delta region. Furthermore, a field-work campaign to monitor salinity affected rice (and a reference site) over a growing season could be used to retrieve further insights into the relation of observed satellite imagery to rice productivity values. Observations can be correlated with weather data and combined with a crop growth model at the level of salinity exposure. The results of this study would allow for precise and targeted crop advice and the ability to predict a yield loss for a particular salinity level [32]. Once the basic set-up is there, more precise data-sources (such as local weather stations) can be integrated.

The social research part will improve by interviewing a more substantial number of farmers with a different interview strategy. Statements proved useful to facilitate discussion. The stack of statements should, however, be smaller and improved translation skills are necessary to interact in the discussion to ask follow-up questions after the farmer has placed the statements in a category. Even though few civil society organizations (NGOs) work independently of the state [52], different routes to reach farmers should be explored which would create more objectivity toward the government. However essential this aspiration is, the author perceives accomplishment will be impossible for foreign (and very likely Vietnamese) researchers in the current administered political context of the MKD.

A

Farmer Survey

Question	**Response**
General Info	
1. # gps waypoint	________________________
Rice crop growth	
2. What is the rice growth stage?	fallow______ bare field/ plouged______ flooded______ transplanted/ emergence______ tillering______ booting______ flowering______ milking______ ripening______ harvested______
3. Indicate rice crop seasons	Winter-Spring (8-12) [DX]______ Spring-Summer (12-3) [XH]______ Summer-Autumn (5-8) [HT]______ Main wet season (coastal areas)______ late (m)______ early______ Other Seasons [Please indicate name + period]_____
4. What is the crop condition?	good______ drought damage______ pest/ disease damage______ flood damage______ salinity damage______ acid soil damage______ Not known______ N/A______
5. Indicate # of seasons/year (type of farming system?)	0______ 1______ 2______ 3______
6. Indicate rice varieties	________________________
7. In what years were you affected by salinity problems?	Never______ last year dry season (2015-2016)______ every year______ other______
8. What is the field size (m2)?	________________________
Irrigation	
9. Date of last irrigation	________________________
10. Date of last harvest	________________________
11. What is the Irrigation water source? (dry season?)	surface water (self-pumped)______ surface water (no pumping)______ ground water (self-pumped)______ Rainfed______
12. What is the maximum salinity tolerance?	________________________
13. Please comment on this statement(s)	When I irrigate my crops, I know exactly the salinity concentration and whether the water quality is good for my crops ______ I irrigate my crops whenever they need water______ When I irrigate my crops in the dry season, I know there is a risk of damaging the crops
Yield	
Indicate Name Season *Indicate Period (month - month)* *Affected by salinity? (Y/N)* 14. Yield of wet rice (kg)/ area(m2) /season 15. Yield of dry rice (kg) / area(m2)/ season 16. Price / 1 kg dry rice (VND/kg)	Season 1 :______ Season 2 :______ Season 3 :______
Other income	
17. Do you receive income from other sources?	No______ Orchards______ Aquaculture______ Livestock______ vegetables______ family______ government______ neighbors______ shop______

Table A.1: Rice farmer survey

B

XGBoost

This explanation on the theory behind the software XGBoost is largely based on the work by Jason Brownlee [8]. An extensive description can be found in the work of the author of XGBoost, Tianqi Chen[12].

XGBoost stands for eXtreme Gradient Boosting, which is a software that supports various objective functions, including regression, classification, and ranking. XGBoost is an implementation of gradient boosted decision trees designed for speed and performance, which explains its popularity in machine learning. The software is used for supervised learning problems, where training data (x_i) is used to predict a target variable (y_i); in this case, the land cover classes of the earth surface [22].

The model in supervised learning refers to the mathematical structure of how to predict y_i given x_i. To find the best parameters (θ) given x_i, an objective function is defined to measure the performance of the model. The objective function is composed of the training loss function (L) and the regularization term (Ω).The training loss measures how predictive our model is on training data. The mean squared error is a frequently used applied technique for this term. The regularization term helps to create a simple and predictive model as it controls the complexity of the model.

$$Obj(\theta) = L(\theta) + \Omega(\theta) \tag{B.1}$$

The tree ensemble model used in XGBoost is a set of Classification And Regression Trees (CART). We classify training data into different leaves (figure B.1), and assign to the input data the score on the corresponding leaf. A, B, C, and D are decisions on attribute values of the satellite input data.

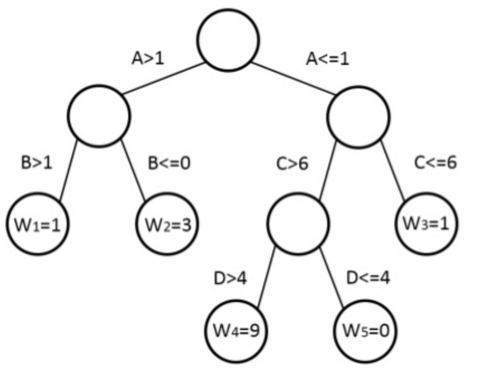

Figure B.1: Tree Building Algorithm.[38]

To represent the complex reality, a tree ensemble model is used which sums the prediction of multiple trees together. For a classification problem, each land use class embodies one tree. The prediction scores of each individual tree are summed up to arrive at the final leaf score. Tree ensembles are precisely the model behind a commonly used learning method for classification, called random forest. The difference between the random forest and XGBoost is the approach to training the model.

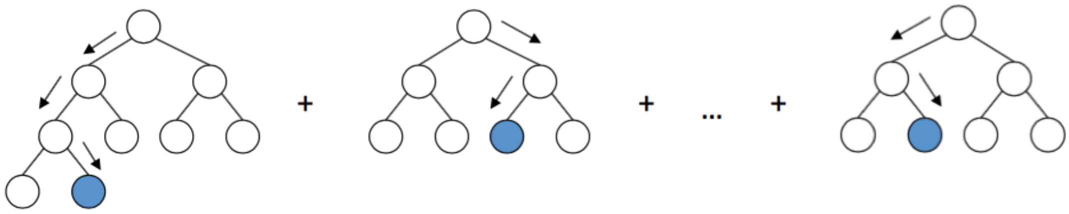

Figure B.2: Tree Ensemble.[70]

The trees are trained by defining an objective function and optimizing it. The parameters of the trees we need to find are functions f_i, which each contain the structure of the tree and the leaf scores. The prediction value $\hat{y}(t)$ is corrected by adding a new tree (or function f_i) in an additive process. The added function that is chosen optimizes the objective function each time and corrects previous errors. This process is called boosting; trees are added sequentially until no further improvements can be made. Using the Mean Squared Error as a loss function, the objective function becomes B.2

$$Obj^{(t)} = \sum_{i=1}^{n} (y_i(\hat{y}_i^{(t1)} + f_t(x_i)))^2 + \sum_{i=1}^{t} \Omega(f_i) \tag{B.2}$$

Besides optimizing the loss function ($L(f)$), the complexity of the tree ($\Omega(f)$) as defined in the regularization function can also be optimized. A definition of the tree $f(x)$ in B.3 helps us to understand its complexity. w is the vector of scores on leaves, q is a function assigning each data point to the corresponding leaf, and T is the number of leaves.

$$f_t(x) = w_{q(x)}, w \in R^T, q : R^d \to \{1, 2, ..., T\} \tag{B.3}$$

After Taylor expansion of the loss function up to the second order and formalizing the tree model, the optimal weight (or vector scores) on each leaf and the resulting objective functions are shown in B.4. G_i and H_i are compressed definitions of the first and second partial derivatives of the training loss function, also called gradient statistics. The objective function in B.4 measures how good a tree structure ($q(x)$) is. The smaller the score, the better the tree structure [13].

$$w_j^* = \frac{G_j}{H_j + \lambda}, Obj^* = \frac{1}{2} \sum_{j=1}^{T} \frac{G_j^2}{H_j + \lambda} + \gamma T \tag{B.4}$$

For a given tree structure, gradients statistics are pushed to the leaves they belong to, summed together and used in the objective formula to calculate how good the tree is. All possible trees should be enumerated and the best one chosen. Since this is unmanageable in practice, the algorithm optimizes one level of the tree at a time. A leaf is split into two leaves (left (L) and right (R) for which formula B.5 presents the score which the leaf gains. γ is an important flag parameter. If the gain is smaller than γ, the branch will not be added to the tree. This is the pruning technique in tree-based models which reduces the size of decision trees by removing sections of the tree that provide little power to classify the input data. XGBoost searches for an optimal split of the leaf scores by scanning the gradient statistics and calculating the structure score of all possible split solutions in an efficient way.

$$Gain = \frac{1}{2}[\frac{G_L^2}{H_L + \lambda} + \frac{G_R^2}{H_R + \lambda} - \frac{(G_L + G_R)^2}{H_L + H_R + \lambda}] - \gamma \tag{B.5}$$

C
Climatology 2x Rice (2)

NDVI values for 2x Rice (2) areas are averaged over week 44, 45 and 46. Each grid cell thus contains an individual average NDVI value. This value is compared against the mean NDVI value of all pixels for the same period. The difference of both is the anomaly NDVI value. The anomaly values are analyzed in a Gaussian distribution and a cumulative distribution curve is plotted (Figure C.1(a)). Positive anomaly values that exceed two standard deviations above the mean value (threshold = 0.25) are mapped in Figure C.1(c)). These areas are concentrated in Long Phu and Chau Thanh districts which have predominantly 3x Rice cropping schedules (Figure E.2). The plausible misclassification as 2x Rice (2) could be due to the distinct first and second rice growth season at these locations The first rice season is short and the second season is not well defined compared to the seasonality of 3x Rice areas.

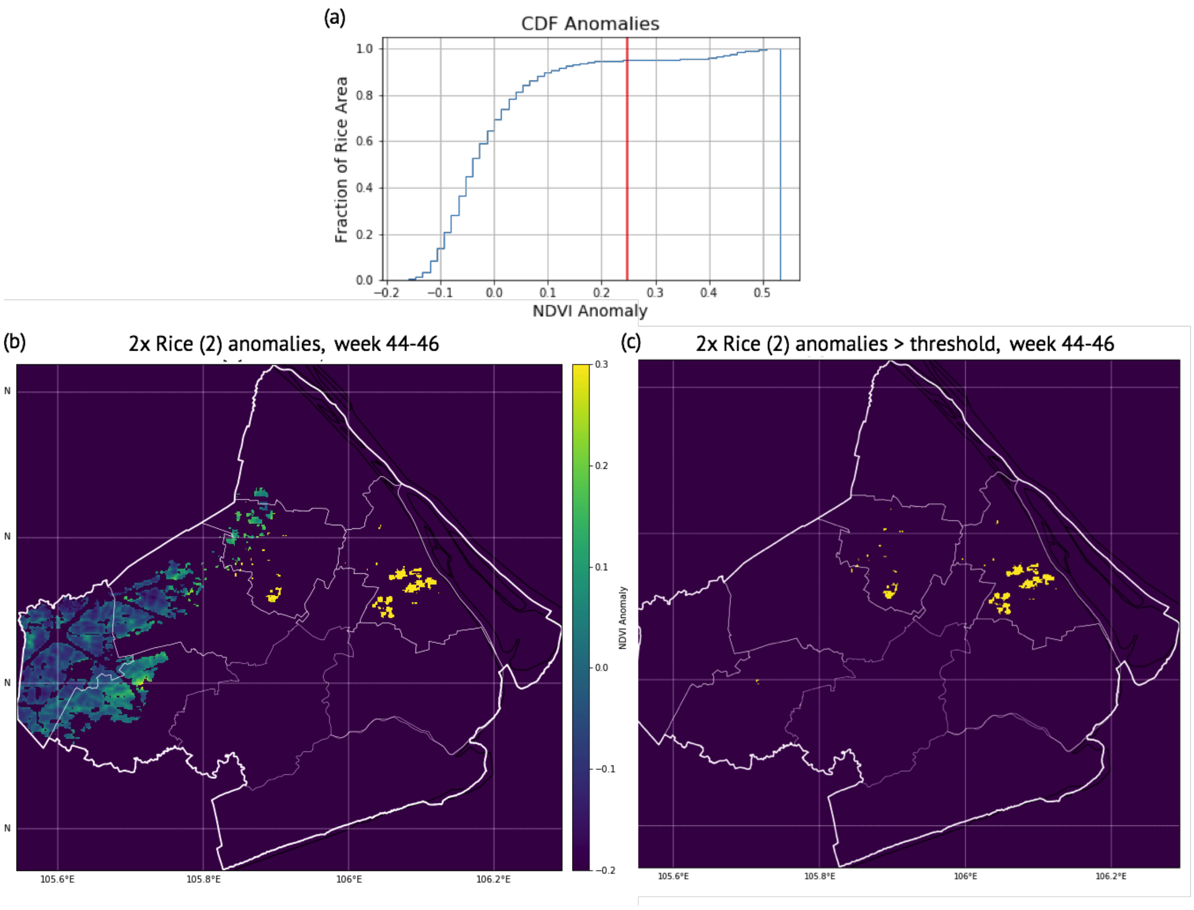

Figure C.1: (a) Cumulative distribution of anomaly values in Week 44-46 for 2x Rice [2] areas. Threshold is set at 0.25 (95%) (b) Anomalies in Week 44-46, (c) Anomalies above threshold (0.25, 95%) in Week 44-46

D

Comparing Rice Areas

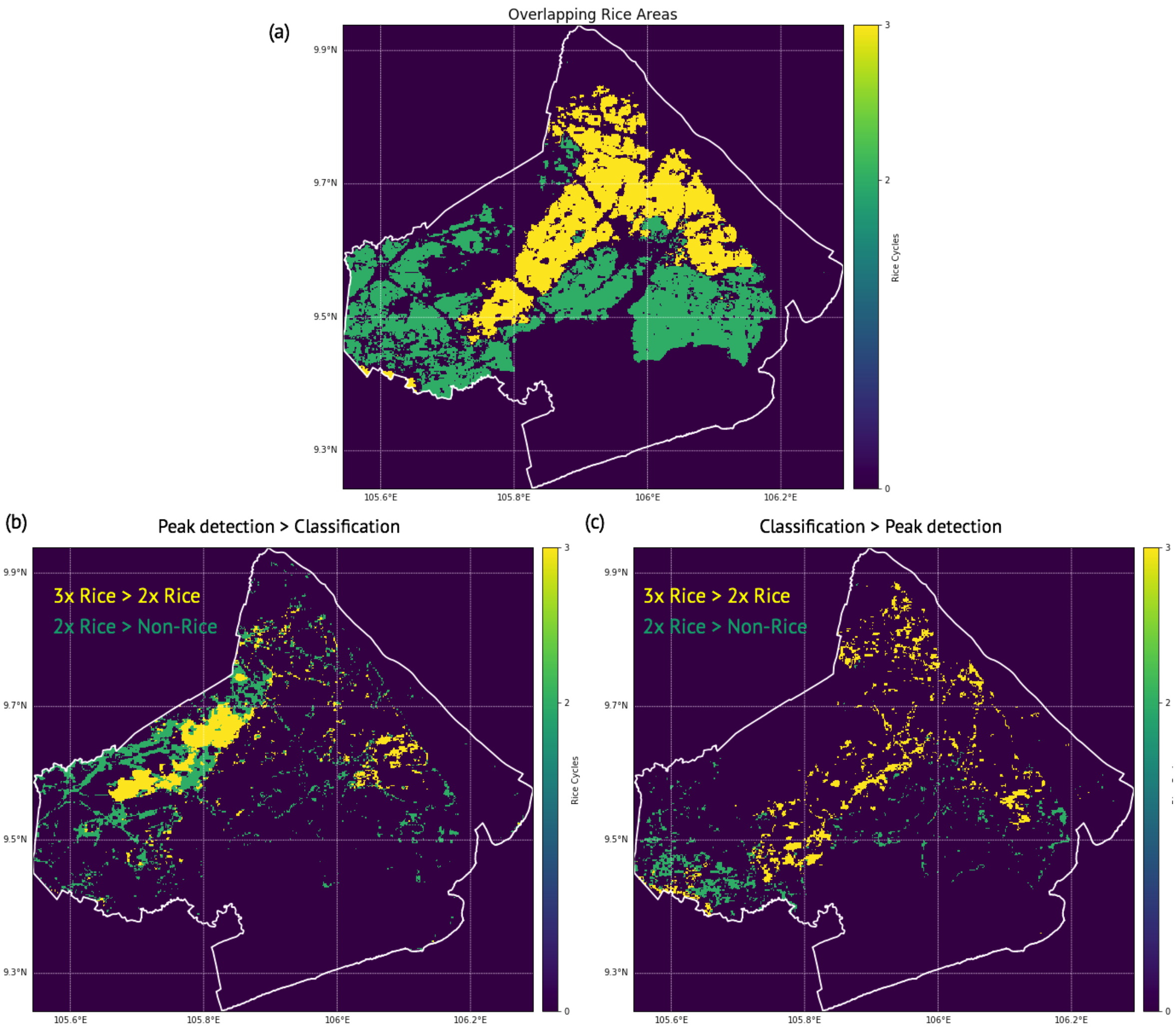

Figure D.1: (a) Overlapping Rice Areas, (b) Peak detection > Classification and (c) Classification > Peak detection

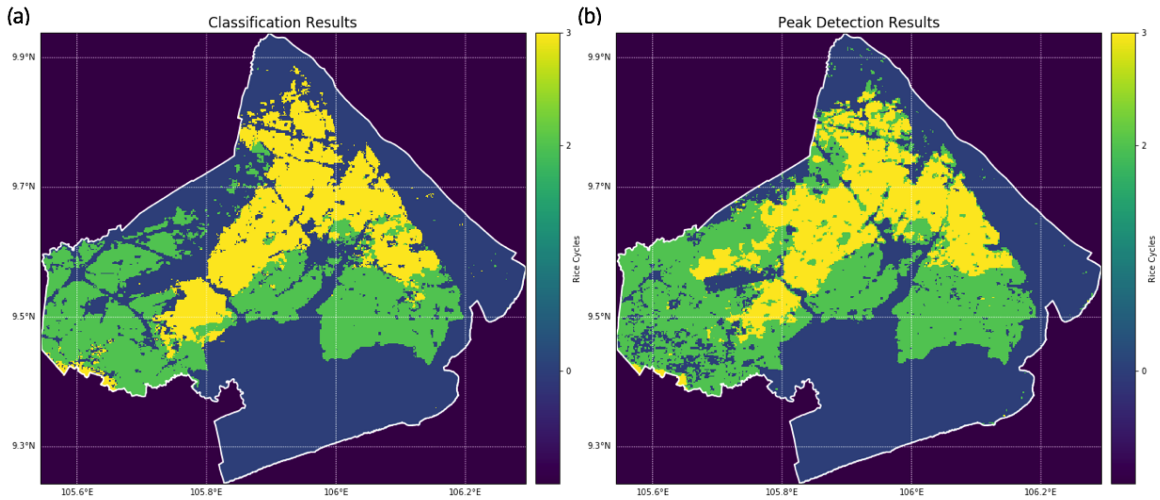

Figure D.2: Rice areas as mapped through (a) supervised classification and (b) peak detection analysis

E

Peak Detection

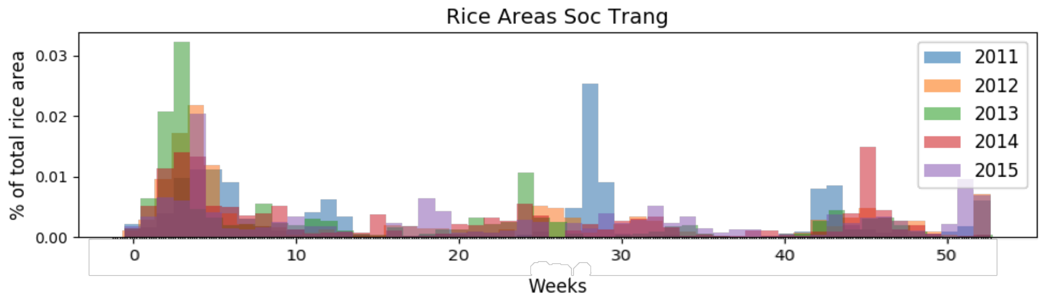

Figure E.1: NDVI peak dates for all districts in Soc Trang Province for 7 years

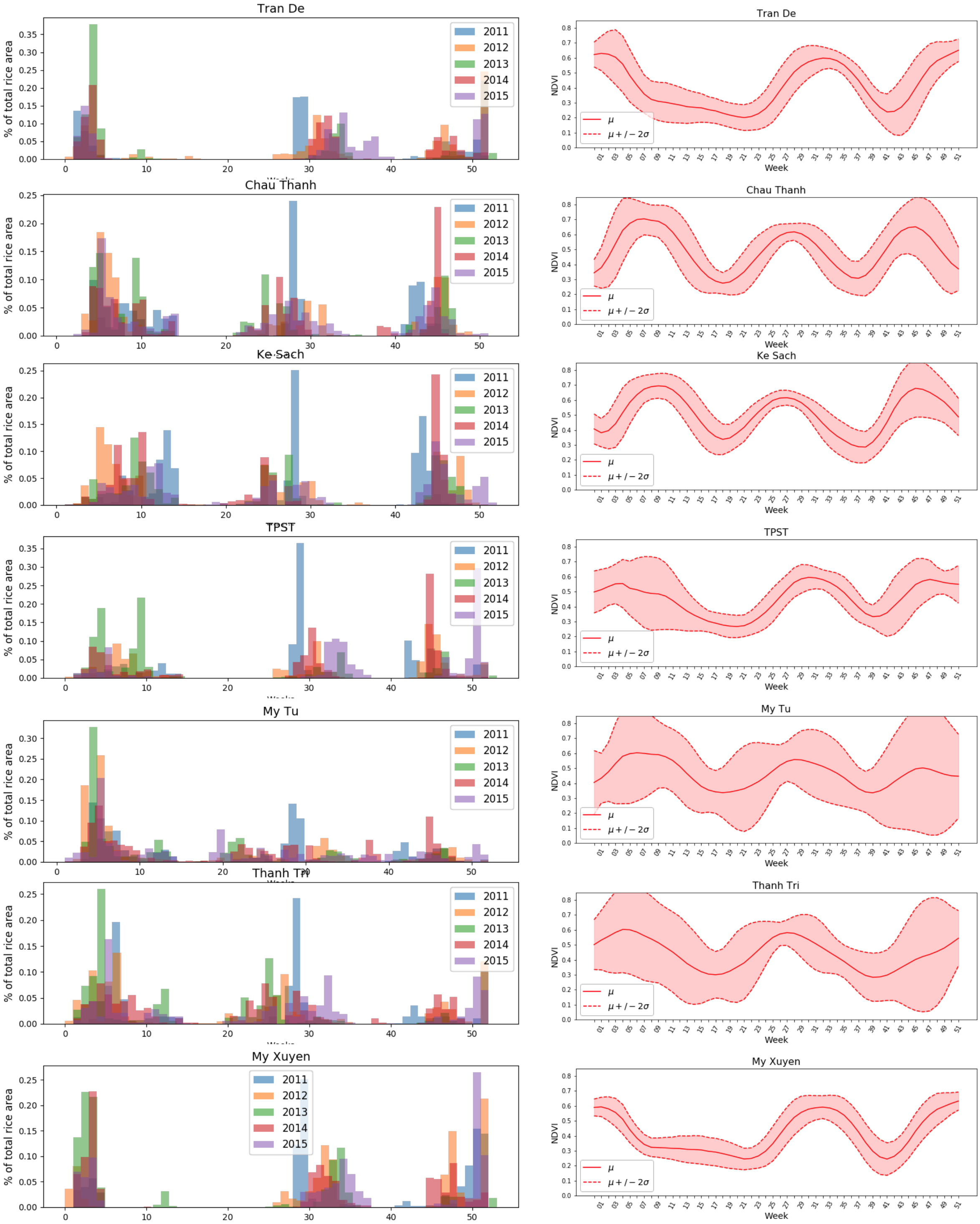

Figure E.2: NDVI peak dates for rice areas of different districts (*left*) and corresponding climatology from 2011 to 2015 (*right*)

F

Government Data Rice Damages

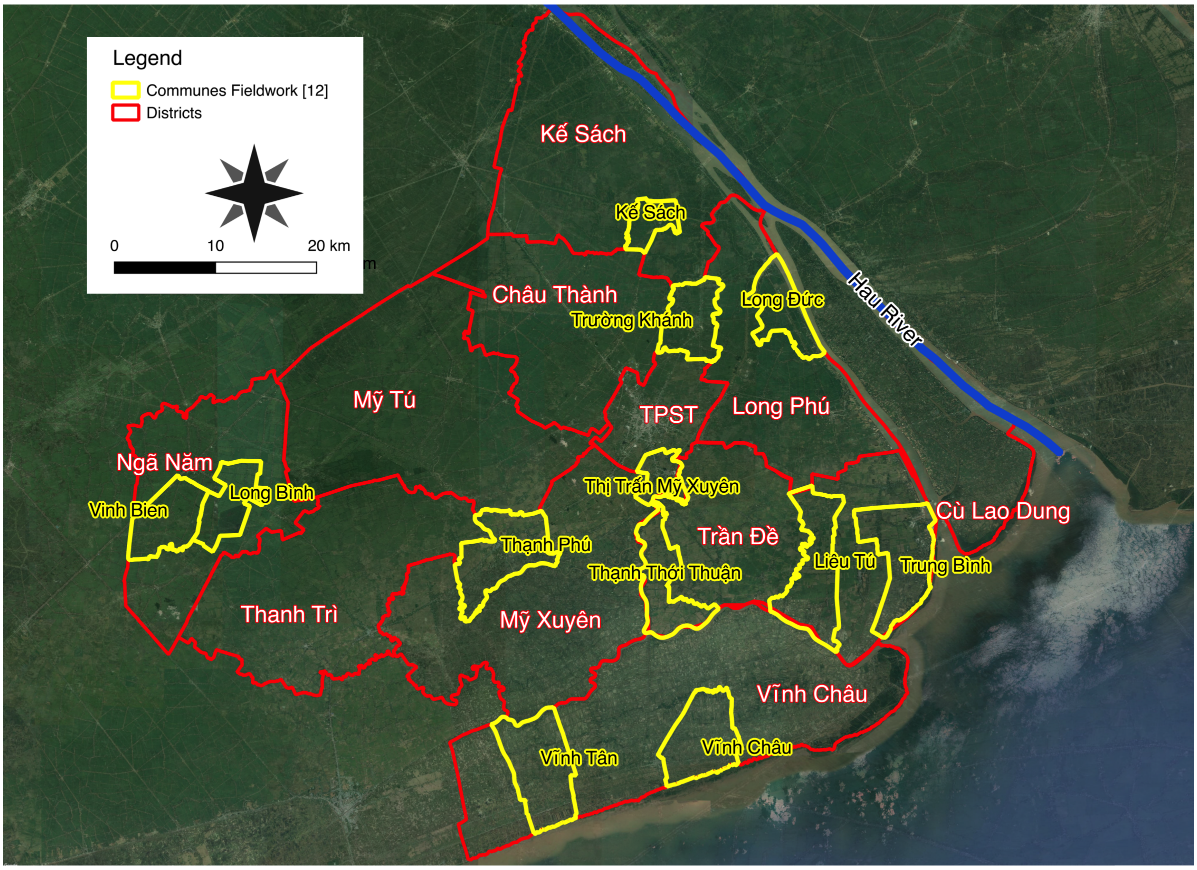

Figure F.1: Visited Communes in Soc Trang Province during Fieldwork

Table F.1 displays affected and total rice areas in visited communes across Soc Trang province (figure F.1) when obtained. In some communes, damages were partitioned into hectares of rice yield affected by different percentages. Table F.2 presents aggregated information about salinity damages from all districts in Soc Trang province. On average, 5-10 different communes form a district and are required to report to the district government about the condition of agricultural production.

		Affected Rice (ha)				
Commune	District	**30-70%**	*>70%*	**Total**	Total Rice (ha)	farming system
Lieu Tu	Tran De	N/A	N/A	N/A	N/A	2x Rice
Trung Binh	Tran De	**613.4**	*31.35*	**645**	N/A	2x Rice
Thanh Thoi Thuan	Tran De	-	-	**300**	2250	2x Rice
Long Duc	Long Phu	-	*600*	**600**	1329	3x Rice
Truong Khanh	Long Phu	**467.98**	*263.07*	**731**	N/A	3x Rice
Ke Sach	Ke Sach	**92.92**	*252.05*	**345**	792	3x Rice
TT my Xuyen	My Xuyen	**53.6**	*6.68*	**72**	460	2x Rice
Thanh Phu	My Xuyen	-	*259*	**259**	1618	2x Rice
Long Bien	Nga Nam	-	-	**100**	1920	2x Rice
Vinh Bien	Nga Nam	-	-	**700**	2800	2x Rice

Table F.1: Reported affected rice areas in visited communes

District	**DX <30%**	**DX 30-70%**	**DX >70%**	**XH <30%**	**XH 30-70%**	**XH >70%**	**Total Affected Rice**	**Other Affected Crops**	**Total Damages ***
Tran De		2146.0	1468.0				3614.1		2663.8
Cu Lao Dung							N/A	Sugarcane (3378.5)	3468.6
Chau Thanh				6845.29	2332.5	3113.7	12291.5		12308.1
Ke Sach		1638.1	1922.7				3560.8	Fruit Trees (507.4)	4096.0
TPST		178.4	59.9			198.3	436.6		445.2
Long Phu		15.3	39.7		1486.1	3210.9	4741.9	Sugarcane (41.0)	4816.5
My Tu					176.0	80.9	256.9		256.9
Nga Nam				XH = HT	246.4	728.4	974.9	Freshwater fish (18.2)	1024.7
Thanh Tri		33.5	16.7		1.0	63.6	116.3		116.3
Vinh Chau							N/A		N/A
My Xuyen	205.4	423.7	286.6				1565.4	Rice-Shrimp (649.8)	1565.4

** includes smaller damages to Vegetables, Orchards and Aquaculture production*

Table F.2: Damages to (rice) crops due salinity in districts of Soc Trang province. Reported in affected hectares and partitioned into percentages of affected rice yield by DARD [16]. DX is short for Đông-Xuân, the Winter-Spring rice season, XH stands for Xuân-Hè, the Spring-Summer rice crop.

Bibliography

[1] AgriInfo. Interpretation of Results of Irrigation Water Analysis and Recommendations, 2015. URL http://www.agriinfo.in/.

[2] Edward J. Anthony, Guillaume Brunier, Manon Besset, Marc Goichot, Philippe Dussouillez, and Van Lap Nguyen. Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports*, 5, 2015. ISSN 2045-2322. doi: 10.1038/srep14745. URL http://www.nature.com/articles/srep14745.

[3] Simon Benedikter. *The Vietnamese Hydrocracy and the Mekong Delta: Water Resources Development from State Socialism to Bureaucratic Capitalism.* 2014. ISBN 978-3-643-90437-9.

[4] M. Boschetti, D. Stroppiana, P. A. Brivio, and S. Bocchi. Multi-year monitoring of rice crop phenology through time series analysis of MODIS images. *International Journal of Remote Sensing*, 30(18):4643–4662, 2009. ISSN 01431161. doi: 10.1080/01431160802632249.

[5] Moncef Bouaziz, Jörg Matschullat, and Richard Gloaguen. Improved remote sensing detection of soil salinity from a semi-arid climate in Northeast Brazil. *Comptes Rendus - Geoscience*, 343(11-12):795–803, 2011. ISSN 16310713. doi: 10.1016/j.crte.2011.09.003.

[6] Alexandre Bouvet, Thuy Le Toan, and Nguyen Lam-Dao. Monitoring of the rice cropping system in the Mekong Delta using ENVISAT/ASAR dual polarization data. *IEEE Transactions on Geoscience and Remote Sensing*, 47(2):517–526, 2009. ISSN 01962892. doi: 10.1109/TGRS.2008.2007963.

[7] Britannica. Mekong River, 2017. URL https://www.britannica.com/place/Mekong-River.

[8] Jason Brownlee. A Gentle Introduction to XGBoost for Applied Machine Learning, 2016. URL https://machinelearningmastery.com/gentle-introduction-xgboost-applied-machine-learning/.

[9] Zhanzhang Cai, Per Jönsson, Hongxiao Jin, and Lars Eklundh. Performance of Smoothing Methods for Reconstructing NDVI Time-Series and Estimating Vegetation Phenology from MODIS Data. *Remote Sensing*, 9(12):1271, 2017. ISSN 2072-4292. doi: 10.3390/rs9121271. URL http://www.mdpi.com/2072-4292/9/12/1271.

[10] CGIAR Research Program on Climate Change Agriculture and Food Security. The drought and salinity intrusion in the Mekong River Delta of Vietnam. Technical Report April, CGIAR Research Centers in Southeast Asia, 2016. URL https://cgspace.cgiar.org/rest/bitstreams/78534/retrieve.

[11] C. F. Chen, N. T. Son, C. R. Chen, L. Y. Chang, and S. H. Chiang. Rice crop mapping using SENTINEL-1A phenological metrics. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2016. doi: 10.5194/isprsarchives-XLI-B8-863-2016.

[12] Tianqi Chen. Introduction to Boosted Trees. *Data Mining with Decision Trees*, pages 187–213, 2014. ISSN 0957-4174. doi: 10.1142/9789812771728_0012.

[13] Tianqi Chen. XGBoost: A Scalable Tree Boosting System, 2016. ISSN 0146-4833. URL http://datascience.la/xgboost-workshop-and-meetup-talk-with-tianqi-chen/.

[14] K. Chumkesornkulkit, T. Kasetkasem, P. Rakwatin, A. Eiumnoh, I. Kumazawa, and C. Buddhaboon. Estimated rice cultivation date using an extended Kalman filter on MODIS NDVI time-series data. *Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2013 10th International*, pages 1–6, 2013. doi: 10.1109/ECTICon.2013.6559573.

[15] Kim Son Dang, Ngoc Que Nguyen, Quang Dieu Pham, Truong Thi Thu Trang, and Melanie Beresford. Rapid growth of selected Asian economies. Lessons and implications for agriculture and food security: Republic of Korea, Thailand and Viet Nam. URL http://www.fao.org/docrep/009/ag089e/AG089E08.htm.

[16] DARD. Damages to Agriculture Production Soc Trang Districts. Technical report, DARD, Soc Trang, 2016.

[17] DARD. Personal Communication, 2017.

[18] Caleb De Bernardis, Fernando Vicente-Guijalba, Tomas Martinez-Marin, and Juan M. Lopez-Sanchez. Estimation of Key Dates and Stages in Rice Crops Using Dual-Polarization SAR Time Series and a Particle Filtering Approach. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8 (3):1008–1018, 2015. doi: 10.1109/JSTARS.2014.2372898.

[19] Caleb De Bernardis, Fernando Vicente-Guijalba, Tomas Martinez-Marin, and Juan Lopez-Sanchez. Particle Filter Approach for Real-Time Estimation of Crop Phenological States Using Time Series of NDVI Images. *Remote Sensing*, 8(7):610, 2016. ISSN 2072-4292. doi: 10.3390/rs8070610. URL http://www.mdpi.com/2072-4292/8/7/610.

[20] Caleb De Bernardis, Fernando Vicente-Guijalba, Tomas Martinez-Marin, and Juan M. Lopez-Sanchez. Contribution to Real-Time Estimation of Crop Phenological States in a Dynamical Framework Based on NDVI Time Series: Data Fusion with SAR and Temperature. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9(8):3512–3523, 2016. ISSN 21511535. doi: 10.1109/JSTARS.2016.2539498.

[21] Deltares and Delta Alliance. Vietnam-Netherlands Mekong Delta Masterplan project Mekong delta water resources assesement studies. *Viet nam-Netherlands Mekong Delta Masterplan projectetherlands Mekong Delta Masterplan project*, pages 1–68, 2011. URL http://nguyenthanhmy.com/courses/GOOD-Mekong-Water-Resource-2011.pdf.

[22] DMLC. Introduction to Boosted Trees: XGBoost 0.6 documentation, 2015. URL http://xgboost.readthedocs.io/en/latest/model.html.

[23] Abd El Kader Douaoui, Hervé Nicolas, and Christian Walter. Detecting salinity hazards within a semiarid context by means of combining soil and remote-sensing data. *Geoderma*, 134(1-2):217–230, 2006. ISSN 00167061. doi: 10.1016/j.geoderma.2005.10.009.

[24] Le Canh Dung, Vo Van Ha, Vo Van Tuan, Dang Kieu Nhan, John Ward, and and Peter Brown. Financial Capacity of Rice-based Farming Households in the Mekong Delta , Vietnam. *Asian Journal of Agriculture and Development*, 14(1):73–87, 2017. URL https://econpapers.repec.org/RePEc:sag:seajad:v:14:y:2017:i:1:p:73-87.

[25] Abdelhamid A. Elnaggar and Jay S. Noller. Application of remote-sensing data and decision-tree analysis to mapping salt-affected soils over large areas. *Remote Sensing*, 2(1):151–165, 2010. ISSN 20724292. doi: 10.3390/rs2010151.

[26] ESA. User Guides Sentinel-2 MSI Revisit and Coverage, . URL https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/revisit-coverage.

[27] ESA. User Guides Sentinel-1 SAR, . URL https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar.

[28] FAO. Rapid growth of selected Asian economies: Lessons and Implications for Agriculture and Food Security. Technical report, 2006.

[29] FAO. Crop and livestock products, 2016. URL http://www.fao.org/faostat/.

[30] FAO. *The future of food and agriculture – Trends and challenges.* 2016. ISBN 9789251095515. doi: ISBN978-92-5-109551-5.

[31] Ramsey Faragher. Understanding the basis of the kalman filter via a simple and intuitive derivation [lecture notes]. *IEEE Signal Processing Magazine*, 29(5):128–132, 2012. ISSN 10535888. doi: 10.1109/MSP.2012.2203621.

[32] Paolo Ficarelli (IRRI). Personal Communication, 2017.

[33] Katie Gallagher and Davina Porock. The Use of Interviews in Q Methodology Card Content Analysis. *Nursing research*, 59:295–300, 2010.

[34] Global Rice Science Partnership (GRiSP). *Rice almanac*. 2013. ISBN 9789712203008. doi: 10.1093/aob/mcg189.

[35] Martin L. Gnyp, Yuxin Miao, Fei Yuan, Susan L. Ustin, Kang Yu, Yinkun Yao, Shanyu Huang, and Georg Bareth. Hyperspectral canopy sensing of paddy rice aboveground biomass at different growth stages. *Field Crops Research*, 155:42–55, 2014. ISSN 03784290. doi: 10.1016/j.fcr.2013.09.023. URL http://dx.doi.org/10.1016/j.fcr.2013.09.023.

[36] Juan Gu, Xin Li, Chunlin Huang, and Gregory S. Okin. A simplified data assimilation method for reconstructing time-series MODIS NDVI data. *Advances in Space Research*, 44(4):501–509, 2009. ISSN 02731177. doi: 10.1016/j.asr.2009.05.009. URL http://dx.doi.org/10.1016/j.asr.2009.05.009.

[37] Jeffrey Hays. Agriculture in Vietnam Facts and Details, 2014. URL http://factsanddetails.com/southeast-asia/Vietnam/.

[38] Tong He. XGBoost: Extreme Gradient Boosting, 2015. URL https://www.youtube.com/watch?v=ufHo8vbk6g4.

[39] Ngu Hieu and Yen Trung. Privatization of State-Owned Enterprises in Vietnam Opportunities and Challenges, 2017. URL https://medium.com/@dataramatech/.

[40] Brent N. Holben. Characteristics of maximum-value composite images from temporal AVHRR data. *International Journal of Remote Sensing*, 7(11):1417–1434, 1986. ISSN 13665901. doi: 10.1080/01431168608948945.

[41] An Hong. Vietnam looks to divest from all agricultural SOEs by 2017, 2016. URL https://e.vnexpress.net/news/business/.

[42] IFAD. Salinity Monitoring and Forecasting in the Mekong Delta. Technical Report August, 2013.

[43] IFAD. Earth Observation support for the international fund for agricultural development. Technical report, 2014. URL http://esamultimedia.esa.int/multimedia/publications/IFAD/.

[44] International Rice Research Institute. Breeding for salt tolerance in rice, 2006. URL http://www.knowledgebank.irri.org/ricebreedingcourse/.

[45] IPCC. *Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel*. 2007. ISBN 9780521880107. doi: 10.1256/004316502320517344.

[46] IRRI. Satellite imagery to soon enable large-scale monitoring of Asia's rice areas, 2015. URL http://irri.org/news/media-releases/satellite-imagery-to-soon-enable-large-scale-monitoring-of-asia-s-rice-areas.

[47] Irri and AfricaRice; Ciat. Global Rice Science Partnership (GRiSP). (November):105, 2010. URL http://irri.org/our-science/global-rice-science-partnership-grisp.

[48] A M Ismail, M J Thomson, G V Vergara, M A Rahman, R K Singh, G B Gregorio, and D J Mackill. Designing Resilient Rice Varieties for Coastal Deltas Using Modern Breeding Tools. In *Tropical Deltas and Coastal Zones. Food Production, Communities and Environment at the Land-Water Interface*, chapter 12. 2010.

[49] Neha Joshi, Matthias Baumann, Andrea Ehammer, Rasmus Fensholt, Kenneth Grogan, Patrick Hostert, Martin Rudbeck Jepsen, Tobias Kuemmerle, Patrick Meyfroidt, Edward T.A. Mitchard, Johannes Reiche, Casey M. Ryan, and Björn Waske. A review of the application of optical and radar remote sensing data fusion to land use mapping and monitoring. *Remote Sensing*, 8(1):1–23, 2016. ISSN 20724292. doi: 10.3390/rs8010070.

[50] Toru Konishi. Climate Change on the Vietnam, Mekong Delta Expected impacts and adaptations. In *World Bank East Asia Infrastructure*, 2011.

[51] Caitlin Kontgis, Annemarie Schneider, and Mutlu Ozdogan. Mapping rice paddy extent and intensification in the Vietnamese Mekong River Delta with dense time stacks of Landsat data. *Remote Sensing of Environment*, 169:255–269, 2015. ISSN 0034-4257. doi: 10.1016/j.rse.2015.08.004. URL http://dx.doi.org/10.1016/j.rse.2015.08.004.

[52] Rose Marie Arvid Larsen, Hans Skaarup Larsen, Sofie Mortensen, and Kristine Juul. *Non-governmental organizations' engagement in Vietnamese Water Management*. PhD thesis, Roskilde University, 2015. URL http://rudar.ruc.dk/handle/1800/22279.

[53] Le Anh Tuan, Chu Thai Hoanh, Fiona Miller, and Bach Tan Sinh. Flood and Salinity Management in the Mekong Delta, Vietnam. In *Challenges to sustainable development in the Mekong delta: Regional and national policy issues and research needs*, chapter 1, pages 15–68. 2007.

[54] Eugene V Maas and Glenn J Hoffman. Crop salt tolerance current assessment. *Journal of the irrigation and drainage division*, 103(2):115–134, 1977.

[55] Mekong River Commission. Physiographic Regions. URL http://www.mrcmekong.org/mekong-basin/physiography/physiographic-regions/.

[56] P.S.J. Minderhoud, G Erkens, V.H. Pham, V.T Bui, L Erban, H. Kooi, and E. Stouthamer. Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta , Vietnam. *Environmental Research Letters*, 12(6), 2017. doi: 10.1088/1748-9326/aa7146.

[57] Ellen Minkman. Personal Communication, 2017.

[58] Ellen Minkman, Maarten van der Sanden, and Martine Rutten. Practitioners' Viewpoints on Citizen Science in Water Management: A Case Study in Dutch Regional Water Resource Management. *Hydrology and Earth System Sciences*, pages 153–167, 2016. ISSN 1607-7938. doi: 10.5194/hess-2016-463.

[59] Mostafa K Mosleh, Quazi K Hassan, and Ehsan H Chowdhury. Application of remote sensors in mapping rice area and forecasting its production: a review. *Sensors (Basel, Switzerland)*, 15(1):769–91, jan 2015. ISSN 1424-8220. doi: 10.3390/s150100769. URL http://www.ncbi.nlm.nih.gov/pubmed/25569753.

[60] Nguyen Nam and Truc Thanh. Vietnam needs independent farmers' associations Social Commentators, 2015. URL http://www.rfa.org/english/news/vietnam/.

[61] Andrew Nelson, Tri Setiyono, Arnel B. Rala, Emma D. Quicho, Jeny V. Raviz, Prosperidad J. Abonete, Aileen A. Maunahan, Cornelia A. Garcia, Hannah Zarah M Bhatti, Lorena S. Villano, Pongmanee Thongbai, Francesco Holecz, Massimo Barbieri, Francesco Collivignarelli, Luca Gatti, Eduardo Jimmy P Quilang, Mary Rose O Mabalay, Pristine E. Mabalot, Mabel I. Barroga, Alfie P. Bacong, Norlyn T. Detoito, Glorie Belle Berja, Frenciso Varquez, Wahyunto, Dwi Kuntjoro, Sri Retno Murdiyati, Sellaperumal Pazhanivelan, Pandian Kannan, Petchimuthu Christy Nirmala Mary, Elangovan Subramanian, Preesan Rakwatin, Amornrat Intrman, Thana Setapayak, Sommai Lertna, Vo Quang Minh, Vo Quoc Tuan, Trinh Hoang Duong, Nguyen Huu Quyen, Duong Van Kham, Sarith Hin, Touch Veasna, Manoj Yadav, Chharom Chin, and Nguyen Hong Ninh. Towards an operational SAR-based rice monitoring system in Asia: Examples from 13 demonstration sites across Asia in the RIICE project. *Remote Sensing*, 6 (11):10773–10812, 2014. ISSN 20724292. doi: 10.3390/rs61110773.

[62] Netherlands Space Office. Sat4Rice (Satellite data for rice farmers in Vietnam). *Netherlands Space Office*, 2016. URL https://g4aw.spaceoffice.nl/files/files/G4AW/projectleaflets/A4leafletSat4RiceLR.pdf.

[63] Duy Ba Nguyen, Alexander Gruber, and Wolfgang Wagner. Mapping rice extent and cropping scheme in the Mekong Delta using Sentinel-1A data. *Remote Sensing Letters*, 7(12):1209–1218, 2016. ISSN 2150-704X. doi: 10.1080/2150704X.2016.1225172. URL https://www.tandfonline.com/doi/full/10.1080/2150704X.2016.1225172.

[64] Thi Thu Ha Nguyen, C. A. J. M. De Bie, Amjad Ali, E. M. A. Smaling, and Thai Hoanh Chu. Mapping the irrigated rice cropping patterns of the Mekong delta, Vietnam, through hyper-temporal SPOT NDVI image analysis. *International Journal of Remote Sensing*, 33(2):415–434, 2012. ISSN 0143-1161. doi: 10.1080/01431161.2010.532826. URL http://www.tandfonline.com/doi/abs/10.1080/01431161.2010.532826.

[65] Szilard Pafka. Benchmarking Random Forest Implementations, 2015. URL http://datascience.la/benchmarking-random-forest-implementations/.

[66] Ambica Paliwal and Alice Laborte. Phenological Response of Rice Crop to Salinity Using Time Series Data. *Asian Association on Remote Sensing*, (1):1–5, 2015. URL http://www.a-a-r-s.org/.

[67] F. Pedregosa, G. Varoquaux, A. Gramfort, V. Michel, B. Thirion, O. Grisel, M. Blondel, P. Prettenhofer, R. Weiss, V. Dubourg, J. Vanderplas, A. Passos, D. Cournapeau, M. Brucher, M. Perrot, and E. Duchesnay. Scikit-learn Machine Learning in Python. *Journal of Machine Learning Research*, 12:2825–2830, 2011.

[68] M. C. Peel, B. L. Finlayson, and T. A. Mcmahon. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11:1633–1644, 2007.

[69] International rivers. Foretelling the Mekong River's Fate: Key Findings of the MRC's Strategic Environmental Assessment on Mekong Mainstream Dams, 2011. URL https://www.internationalrivers.org/.

[70] Alex Rogozhnikov. Gradient Boosting explained [demonstration], 2016. URL http://arogozhnikov.github.io.

[71] Toshihiro Sakamoto, Masayuki Yokozawa, Hitoshi Toritani, Michio Shibayama, Naoki Ishitsuka, and Hiroyuki Ohno. A crop phenology detection method using time-series MODIS data. *Remote Sensing of Environment*, 96(3-4):366–374, 2005. ISSN 00344257. doi: 10.1016/j.rse.2005.03.008.

[72] Toshihiro Sakamoto, Cao Van Phung, Aikihiko Kotera, Khang Duy Nguyen, and Masayuki Yokozawa. Analysis of rapid expansion of inland aquaculture and triple rice-cropping areas in a coastal area of the Vietnamese Mekong Delta using MODIS time-series imagery. *Landscape and Urban Planning*, 92(1): 34–46, 2009. ISSN 01692046. doi: 10.1016/j.landurbplan.2009.02.002.

[73] B.P. Salmon, J.C. Olivier, W. Kleynhans, K. J. Wessels, and F. van den Bergh. Improving NDVI time series class separation using and extended Kalman filter. *IEEE Geoscience and Remote Sensing Letters*, pages 43–46, 2010.

[74] Charles W. Schmidt. Delta subsidence: An imminent threat to coastal populations. *Environmental Health Perspectives*, 123(8):A204–A209, 2015. ISSN 15529924. doi: 10.1289/ehp.123-A204.

[75] Vincent Schut (Satelligence). Personal Communication, 2017.

[76] Fernando Sedano, Pieter Kempeneers, and George Hurtt. A Kalman filter-based method to generate continuous time series of medium-resolution NDVI images. *Remote Sensing*, 6(12):12381–12408, 2014. ISSN 20724292. doi: 10.3390/rs61212381.

[77] Rakesh Kumar Singh, Edilberto Redoña, and Luzminda Refuerzo. *Varietal Improvement for Abiotic Stress Tolerance in Crop Plants: Special Reference to Salinity in Rice*, pages 387–415. Springer Netherlands, Dordrecht, 2010. ISBN 978-90-481-3112-9. doi: 10.1007/978-90-481-3112-9_18.

[78] A. Smajgl, T. Q. Toan, D. K. Nhan, J. Ward, N. H. Trung, L. Q. Tri, V. P. D. Tri, and P. T. Vu. Responding to rising sea levels in the Mekong Delta. *Nature Climate Change*, 5(2):167–174, 2015. ISSN 1758-678X. doi: 10.1038/nclimate2469. URL http://www.nature.com/doifinder/10.1038/nclimate2469.

[79] SMILE. Classification Statistical Machine Intelligence and Learning Engine. URL https://haifengl.github.io/smile/classification.html.

[80] N. T. Son, C. F. Chen, C. R. Chen, V. Q. Minh, and N. H. Trung. A comparative analysis of multitemporal MODIS EVI and NDVI data for large-scale rice yield estimation. *Agricultural and Forest Meteorology*, 197:52–64, 2014. ISSN 01681923. doi: 10.1016/j.agrformet.2014.06.007. URL http://dx.doi.org/10.1016/j.agrformet.2014.06.007.

[81] The Socialist Republic of Vietnam; the Kingdom of the Netherlands. Mekong Delta Plan. Technical Report December, 2013.

[82] Toui Tre. Major rivers of Vietnam's Mekong Delta become unusually deeper, 2016. URL https://www.mekongeye.com/2016/08/18/major-rivers-of-vietnams-mekong-delta-become-unusually-deeper/.

[83] Nguyen Do Anh Tuan. Vietnam's Agrarian Reform, Rural Livelihood and Policy Issues. pages 1–19, 2010. URL http://www.rimisp.org/.

[84] United Nations. Viet Nam Emergency Response Plan 2016. 2016. URL https://reliefweb.int/report/viet-nam/viet-nam-emergency-response-plan-201617.

[85] Fernando Vicente-Guijalba, Tomas Martinez-Marin, and Juan M. Lopez-Sanchez. Crop phenology estimation using a multitemporal model and a kalman filtering strategy. *IEEE Geoscience and Remote Sensing Letters*, 11(6):1081–1085, 2014. ISSN 1545598X. doi: 10.1109/LGRS.2013.2286214.

[86] Fernando Vicente-Guijalba, Tomas Martinez-Marin, and Juan M. Lopez-Sanchez. Dynamical Approach for Real-Time Monitoring of Agricultural Crops. *IEEE Transactions on Geoscience and Remote Sensing*, 53(6):3278–3293, 2015. ISSN 01962892. doi: 10.1109/TGRS.2014.2372897.

[87] Vietnam Breaking News. Saline intrusion affects rice production in Soc Trang, 2016. URL https://www.vietnambreakingnews.com/2016/02/saline-intrusion-affects-rice-production-in-soc-trang/.

[88] Vietnam Briefing. Vietnam to Divest in 406 State Owned Enterprises by 2020, 2017. URL http://www.vietnam-briefing.com/news/vietnam-sell-stakes-137-state-owned-enterprises-2020.html/.

[89] Lin Wang, Fu Cun Zhang, Yuan Shu Jing, Xiao Dong Jiang, Shen Bin Yang, and Xiao Mei Han. Multi-temporal detection of rice phenological stages using canopy stagespectrum. *Rice Science*, 21(2):108–115, 2014. ISSN 16726308. doi: 10.1016/S1672-6308(13)60170-5.

[90] Simon Watts and Paul Stenner. Doing Q methodology: theory, method and interpretation. *Qualitative Research in Psychology*, 2(1):67–91, 2005. doi: 10.1191/1478088705qp022oa. URL https://doi.org/10.1191/1478088705qp022oa.

[91] M Wilder and N T Phuong. The status of aquaculture in the Mekong Delta region of Vietnam: Sustainable production and combined farming systems. *Fisheries Science*, 68:847–850, 2002. doi: 10.2331/fishsci.68.sup1_847.

[92] Michaël Witter. Integrated water resources management in the red river basin, Vietnam. A Critical Institutionalist Analysis. 2016. URL https://wlemekong.wikispaces.com/file/view/ThesisMichaelWITTER.pdf/584237435/ThesisMichaelWITTER.pdf.

[93] World Bank. Socialist Republic of Vietnam VDR: Agricultural Modernization. page 33, 2016. URL http://documents.worldbank.org/curated/en/923211468310487558/pdf/VDR-report-word-version.pdf.

[94] Xinhua. Vietnam's Mekong Delta rice output drops, 2016. URL http://news.xinhuanet.com/english/.

[95] Geli Zhang, Xiangming Xiao, Jinwei Dong, Weili Kou, Cui Jin, Yuanwei Qin, Yuting Zhou, Jie Wang, Michael Angelo Menarguez, and Chandrashekhar Biradar. Mapping paddy rice planting areas through time series analysis of MODIS land surface temperature and vegetation index data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 106:157–171, 2015. ISSN 09242716. doi: 10.1016/j.isprsjprs.2015.05.011. URL http://dx.doi.org/10.1016/j.isprsjprs.2015.05.011.