The Effectiveness of Policy Implementation in the Forest Management Zones in Ca Mau, Vietnam

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May, 2023

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ABSTRACT

This Master's research investigates the effectiveness of policies within the mangrove forest management zones, namely the production and protection zones, in Ca Mau Province, Vietnam. The study specifically focuses on the integration of mangrove-shrimp farming and the implementation of on-farm mangroves by farmers. Despite the prevalence of these forest management zones, mangrove deforestation continues to be a concern. The research employs various methods, including a comprehensive review of policy literature, remote sensing-based image analysis using Quickbird and GeoEye imagery, and survey analysis. The policy-literature review reveals a complex landscape of overlapping policies. The image analysis results indicate no discernible difference in the implementation of on-farm mangrove cover between the production and protection zones. Moreover, the survey analysis highlights a convergence of perceptions among farmers in these zones, indicating a blurring of the once-distinct boundaries. These findings underscore the increasing inefficiency of the current forest management zones in Ca Mau and emphasize the urgent need for simplified jurisdictional systems and streamlined variables to promote effective mangrove management. Such efforts are crucial for the global mitigation of mangrove deforestation.

Keywords: integrated mangrove-shrimp farming, Ca Mau Province, Vietnam, policy effectiveness, mangrove cover, protection forest, production forest

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LIST OF ACRONYMS

AIPP: Asia Indigenous Peoples Pact

BZ: Buffer Zone

DARD: Department of Agriculture and Rural Development

DONRE: Department of Nature Resources and Environment

ESA: European Space Agency

EZ: Economic Zone

FAO: Food and Agriculture Organization

FIPI: Forest Inventory and Planning Institute

FORMIS: Forestry Sector Monitoring Information System

FPDL: Forest Protection and Development Law

FPZ: Full Protection Zone

GDLA: General Department of Land Administration

GE(E): Google Earth (Engine)

MARD: Ministry of Agriculture and Rural Development

MONRE: Ministry of Natural Resources and Environment

NIR: Near Infra Red

PES: Payment for Ecosystem Services

PFES: Payment for Forest Ecosystem Services

REDD(+): Reducing Emissions from Deforestation and Forest Degradation

SIWRP: Sub-Institute for Water Resources Planning (Vietnam)

SNV: Stichting Nederlandse Vrijwilligers

VND: Vietnamese Dong

1. INTRODUCTION

Mangroves provide vital ecosystem services that add to the resilience of an area, such as enforcing coastal protection with their complex root systems, supporting biodiversity, and providing goods like food and materials for trade, water purification, carbon sequestration, medicine, and tourism (Ahmed et al., 2017; Toosi et al., 2019). Ecosystem services refer to the environmental properties of an ecosystem's structures and processes. These properties are beneficial and essential products and outcomes that arise from intricate ecological interactions and contribute to human well-being (Chicharo et al., 2015). Despite their usefulness, mangroves are under heavy stress and are considered one of the world's most threatened tropical ecosystems (Acharya, 2016). The current mangrove ecosystems store over 21 gigatons of CO_2 as blue carbon and, therefore, continuous deforestation could impact the climate immensely (Siikamäkii et al., 2012). There is a global call to restore and recover mangroves, support the coastal communities, provide jobs and food security, and aid in global climate mitigation (Spalding & Lael, 2021). This introduction aims to sketch an outline of the current wicked problem regarding the stagnation of mangrove restoration and conservation in Southern Vietnam. The content of the introduction might seem superfluous, but it is merely to outline the essential facets of the wickedness of this research, as further explained in Section 1.6.

1.1. Mangrove decline due to shrimp farming practices

Commodities (a combination of rice, shrimp, and oil palm cultivation) was the primary global driver of mangrove loss, constituting 47% of global losses from 2000 to 2016. The most significant global anthropogenic loss (+- 80%) was concentrated in Southeast Asia due to high mangrove conversions to aquaculture (Goldberg et al., 2020). This is in line with several other studies on the biggest anthropogenic loss hotspot, which is shown to be located across Southeast Asia (Das et al., 2020; Ha et al., 2012a; Liu et al., 2020). Vietnam is the world’s third-largest producer of aquaculture products (Nguyen et al., 2021b). Rising global food demand causes traditional shrimp farms to convert towards highly intensive shrimp farming production. This reduces the area of mangrove forests in Vietnam to make place for bigger and more shrimp farms (Nguyen & Parnell, 2019). Research of the Global Mangrove Watch showed that the extent of mangroves in Vietnam has been declining since 1996, with an average of 90 km^2 yearly since 2010 (Bunting et al., 2018). Unregulated logging of mangroves persists (Stoop et al., 2015), with a number of 30,000 to 50,000 forest violations occurring annually in Vietnam (Forest Legality Initiative, 2014). Mangrove logging to make place for (more intensive) shrimp farming is the main cause of this. The Mekong Delta in Southern Vietnam is the largest remaining mangrove forest, accounting for nearly 89% of all shrimp produced. Located within are the top five producing Provinces: Ca Mau, Bac Lieu, Soc Trang, Ben Tre, and Kien Giang (Baumgartner & Nguyen, 2017; Hauser et al., 2017). The combination of increasing global food demands and these poor shrimp cultivation practices has led to ecosystems' degradation, waterways' pollution, and negative impacts on local communities (Baumgartner & Nguyen, 2017). Aside from the significant economic benefits of shrimp farming, major environmental and social impacts cause shrimp farming to be criticised (Ahmed et al., 2017).

Unsustainable shrimp farming practices in Vietnam resulted in disease outbreaks and significant national income losses, leading governments and non-governmental actors worldwide to push for stricter food safety and social and environmental certification standards (Xuan et al., 2021). The Vietnamese Government has developed legal instruments that assist in protecting, managing, and developing current mangroves while promoting shrimp farming practices (Nguyen et al., 2017).

1.2. Vietnamese national action plan for sustainable aquaculture

Vietnam created a National Master Plan in 2018 to develop the country into a high-income, equitable, democratic, and civilised society by 2050. The plan focuses on a rational spatial arrangement, critical development perspectives, efficient use of natural resources, modern infrastructure, and harmonious development of urban and rural areas. This Master plan covers all sectors of the Vietnamese Government, with dedicated sectoral Master Plans. The National action plan for sustainable aquaculture in 2018 was released to encourage shrimp farmers to transition towards more sustainable production practices and to encourage the implementation of a (sustainable) eco-certification system (Bosma et al., 2016; Ngoc et al., 2021). This plan aims to increase the competitiveness and efficiency of the aquaculture sector. Connecting production and trade will reduce poverty and increase food security, aligning with the global trend of sustainable intensification (Gann et al., 2019; Xuan et al., 2021). The government of Vietnam stated that super-intensive production is the way forward to increase production and meet projected national export targets (Nguyen et al., 2019). This plan focuses on increasing production in combination with ecological and organic shrimp farming principles. Under the motto of 'producing more using less,' the Vietnamese Government aims to use fewer resources, like land, freshwater, and energy, while intensifying production by focusing on social acceptance by implementing eco-certification standards. Mangrove-shrimp farming has been put forward as a solution (Xuan et al., 2021).

As mangroves can provide critical habitat for shrimp, such as feedstock, organic detritus, and shelter, this could create a beneficial co-existence between shrimp and mangroves. A mangrove-shrimp farming system is an eco-friendly approach to ease the land use conflict between mangrove conservation and shrimp farming in the Vietnamese Mekong Delta (Ha et al., 2012a). A mangrove-shrimp farming system combines shrimp production ponds with mangroves in (on bunds or platforms) and around shrimp farming ponds (Nguyen et al., 2018), forming a whole new shrimp production system (Tran et al., 2021).

1.3. Shrimp farming management types

Shrimp farming practices have different management types, consisting of a spectrum between intensive to improved extensive and extensive practices. Many combinations are possible, and thus classification of shrimp farming practices is fuzzy. The general classification is based on pond facilities, stocking density, food supply, water management, level of investment, yield, production techniques, and experience and skills of the farmer (Apud, 1984; Ha et al., 2012b). The main shrimp farming techniques present in the Mekong Delta are the intensive, extensive, and newly introduced mangrove-shrimp farming systems (Joffre et al., 2015).

Intensive shrimp farms are developed to maximise production and depend on manufactured pellets for feeding the shrimp. Farmers manage the production risk by closing the production system from the surrounding environment, managing the water quality in the ponds, and avoiding disease-related infections. In addition, they have high stocking densities, chemical inputs, and mechanical aeration (Joffre et al., 2015; Joffre et al., 2018a), and farmers clean and dry the pond thoroughly after a harvest, remove the debris and try to control the water pH and salinity (Ha et al., 2014). Extensive shrimp farms, contrarily, open sluice gates to use tidal water to catch wild fish, shrimp, and crab, mixed with the frequent artificial stocking of giant black tiger shrimp (*Penaeus monodon*) at low densities (Ha et al., 2012a). Extensive shrimp farms use a limited amount of inputs (fertiliser), no aeration, and only limited to no supplemental feed, depending on the biological productivity of the pond (Joffre et al., 2018a, 2018b). Extensive shrimp farms harvest yearly multiple times to decrease disease risk (Ha et al., 2014). Vietnam additionally introduced the aforementioned mangrove-shrimp farming systems, which resemble extensive shrimp farming, but combine it with mangroves (Nguyen et al., 2018). In general, mangrove-shrimp farming requires less financial input in the form of feed, shrimp larvae, chemicals, and mechanical aeration. Research showed that mangrove-shrimp systems resulted in more wild shrimp and fish than systems without mangroves, like extensive systems. Mangrove-shrimp farming provides more benefits for small-scale farmers than intensive farming systems, such as the decreased risk of disease outbreaks. The shrimp are also more enormous and thus sold for a higher price (Nguyen & Nguyen, 2022). Shrimp farmers, both in extensive and integrated mangrove-shrimp farming, open their sluice gates during high tide[1] to allow seawater to enter and during low tide to release excess water and waste. The frequency of opening the sluice gates varies based on the size and type of farm, stage of shrimp growth, weather and tidal conditions, and individual needs. Mangroves are (re-) planted on-farm by growing mangrove propagules[2] in nurseries and planting them on mudflats at low tide (Virdis, 2014). These propagules grow into mature trees within 10 to 20 years (Stringer, 2023). See Table 1 below for an overview of the main characteristics of the different shrimp farming techniques. Propagules can indicate a farmer's intention to grow mangroves.

Table 1 Shrimp farming practices and their characteristics (Ca Mau) (adapted from Ha, 2015)

Characteristics	Intensive shrimp farming	Extensive shrimp farming	Mangrove-shrimp farming
Shrimp seed	Seed supplements	Mostly from wild stock (occasionally seed supplements)	Mostly from wild stock
Shrimp seed density (individual/m^2)	60-70	1	6-8
Food source	Artificial food	Mulch from decaying leaves of mangroves	Mulch from decaying leaves of mangroves only
Yield (kg/ha/yr)	8,000-10,000	100-150	250-300

Mangrove-shrimp farming systems can be found in either integrated (mixed), associated, or separate mangrove-shrimp farms. Integrated mangrove-shrimp farms include water canals between the strips of mangroves (600-700 m long, 3-6 m wide) (Ha, 2012a). Associated mangrove-shrimp farms have an association function between the pond water and the mangrove. Both integrated and associated often have their mangrove areas surrounded by pond water. Separated mangrove-shrimp farms have a clear distinction between the pond water and the mangrove area (Bosma et al., 2016); see Figure 1 below. In Vietnam, taxes are paid on the width of the parcel, so shrimp farms are often long and narrow (personal communication with an anonymous shrimp farmer, April, 2022).

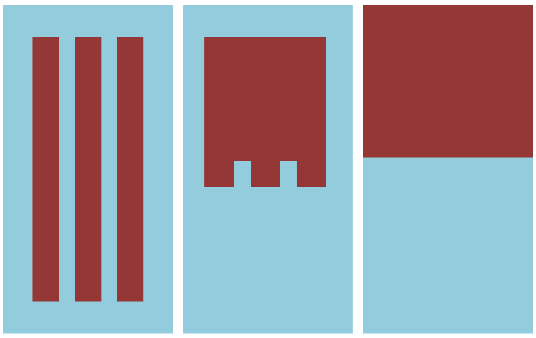

Figure 1 Simplification of integrated (left), associated (middle) and separated (right) mangrove-shrimp farming systems (adapted from Bosma et al., 2016)

[1] Often during spring tide, which is the tide during new and full moon. Spring tide is twice a months and is sign
[2] Seedlings of mangroves

1.3.1. Mangrove ecosystem services in mangrove-shrimp farming

Mangrove-shrimp farming practices create a fragile ecosystem with various interactions between mangroves and shrimp. Therefore, to restore mangroves successfully, it is crucial to have knowledge of their ecology (Stoop et al., 2015). In addition, a shift to sustainable aquaculture will enhance the resilience of mangrove ecosystems (Engle & Van Senten, 2022). Mangrove-shrimp farming practices have both positive and negative influences. The construction of shrimp ponds can fragment the landscape, negatively affecting the ecosystem services provided by mangrove forests (Jonell & Henriksson, 2015). The growth of the aquacultural sector changes the ecosystem services of mangroves, and the outflow of water from farms disturbs the natural balance (Das et al., 2020). Moreover, converting mangroves for economic activities could harm shrimp farming by disrupting their habitat, causing production instability, and increasing disease susceptibility (Ha et al., 2012a, 2012b).

Mangrove leaves contain compounds like phenols and tannins, and when excreted, these can be toxic to *Penaeus monodon* (Fitzgerald, 2000). Decomposed mangrove leaves (peat) can become organic fertiliser that benefits the growth of natural food for the shrimp if the water exchange is sufficient (Rejeki et al., 2019). Moreover, peat formation increases carbon sequestration and storage (Ezcurra et al., 2016). It also provides nutrients as natural food for shrimp in mixed aquaculture. Nevertheless, peat accumulation can consume dissolved oxygen, reducing water and sediment quality resulting in decreasing natural food supply in ponds. This will hinder shrimp growth and results in lower productivity (Do & Dang, 2022). Hence, shrimp ponds with more mangrove trees may have a higher litter load, thus causing peat oxidation and output risk. Mangrove trees older than seven years might provide fewer nutrients to shrimp than their younger counterparts. Hence, the existence of mangrove forests may contribute to reduced yield and increased production risks in aquaculture (Binh et al., 1997).

Mangrove root systems filter out pollutants, decrease salinity and turbidity, and reduce tidal water flow, leading to sediment deposition. The value of wastewater treatment via mangrove forests outweighs the expense of setting up a new wastewater treatment system (Costanza et al., 1997). Thus, mangroves may reduce shrimp farming production risks caused by poor water quality. Moreover, mangrove areas increase seed availability, improve output, and decrease production risk in aquaculture by sheltering against adverse conditions. However, predators of shrimp and mollusc species that are also attracted to the shelter can reduce plankton and benthic algae, threatening the life of juvenile shrimp. Nevertheless, these predators and other species present in mixed aquaculture, such as crabs and fish, can serve as a food source for shrimp. Higher mangrove coverage in farms reduces the possibility of shrimp feed shortage, reducing output fluctuations and uncertainty whilst increasing productivity (Do & Dang, 2022).

1.3.2. Actors involved in mangrove forest management

In Vietnam, the forest consists of terrestrial and mangrove forests, covering 13 million ha, and to both, the same Laws and regulations apply (Hawkins et al., 2010). The management of mangrove forests in Vietnam has been subject to various management structures relating to private, state, and common property, as well as forest contracting (Tan, 2005; Ha et al., 2014). The current legal framework in Vietnam stipulates that the people own land and forest resources, and the State acts as the people's representative and holds ultimate management authority.

The management of mangrove-shrimp farming is regulated at both the national and regional levels, with the Ministry of Agriculture and Rural Development (MARD) and the Ministry of Natural Resources and Environment (MONRE) overseeing national objectives, strategies, institutional structures, and Laws

(Christensen et al., 2008). National-level and regional-level management can significantly impact farmers' day-to-day activities and thus their maintenance of mangroves on-farm in the different management zones (see Appendix A Figure 45 for an extensive overview). The MARD is responsible for forest planning and change monitoring of forest conditions, while the Forest Inventory and Planning Institute (FIPI) and the Forest Protection Department handle forest planning and monitoring tasks, respectively (Tan, 2005). The MONRE manages biodiversity and the land under all forests (Pham et al., 2019). The responsibilities of MARD and MONRE overlap significantly, confusing stakeholders regarding managing mangroves (Hawkins et al., 2010). MARD and MONRE are primarily responsible for the jurisdiction over mangroves, along with the People's Committees. The People's Committees represent the executive branch of the State at the Province, district, and commune levels (Hawkins et al., 2010).

The Department of Agriculture and Rural Development (DARD) and the Department of Nature Resources and Environment (DONRE) serve as provincial counterparts of MARD and MONRE, respectively. The state-owned DARD manages the mangrove forest in Ca Mau Province (justification for study area selection in Chapter 3). They manage agricultural and rural development activities, including forestry and forest management (Vo et al., 2013). Government agencies, including the DARD, Forest Management Boards, and Forest Companies[3], manage special-use, protection, and production forests in Ca Mau. Forest Management Boards are involved in activities related to forest management, including planning, monitoring, and enforcement of regulations related to forest use at the provincial and district levels. The DARD provides technical assistance and support to Forest Management Boards for sustainable forest management. Forest Companies are commercial entities involved in managing and utilising forest resources. The DARD works closely with Forest Companies to ensure their activities align with national and provincial forest management and conservation policies. The DARD also raises awareness among Peoples Committees about sustainable forest management practices and provides technical assistance and support for community-based forest management initiatives. The Provincial Department of Culture, Sports, and Tourism manages national parks in Ca Mau. The DARD ensures that park management is integrated with broader efforts to manage forest resources in the Province (MONRE, 2013). Scientific research and armed force units monitor and enforce forest management regulations in Ca Mau. The DARD provides technical assistance and support to these organisations to help them carry out their roles effectively. The mangrove forest jurisdiction is very complex; see Figure 2 below.

[3] Since 2006 State Forest Enterprises have changed to State-Owned Forest Companies (Forest Companies), where the companies post their own business independently.

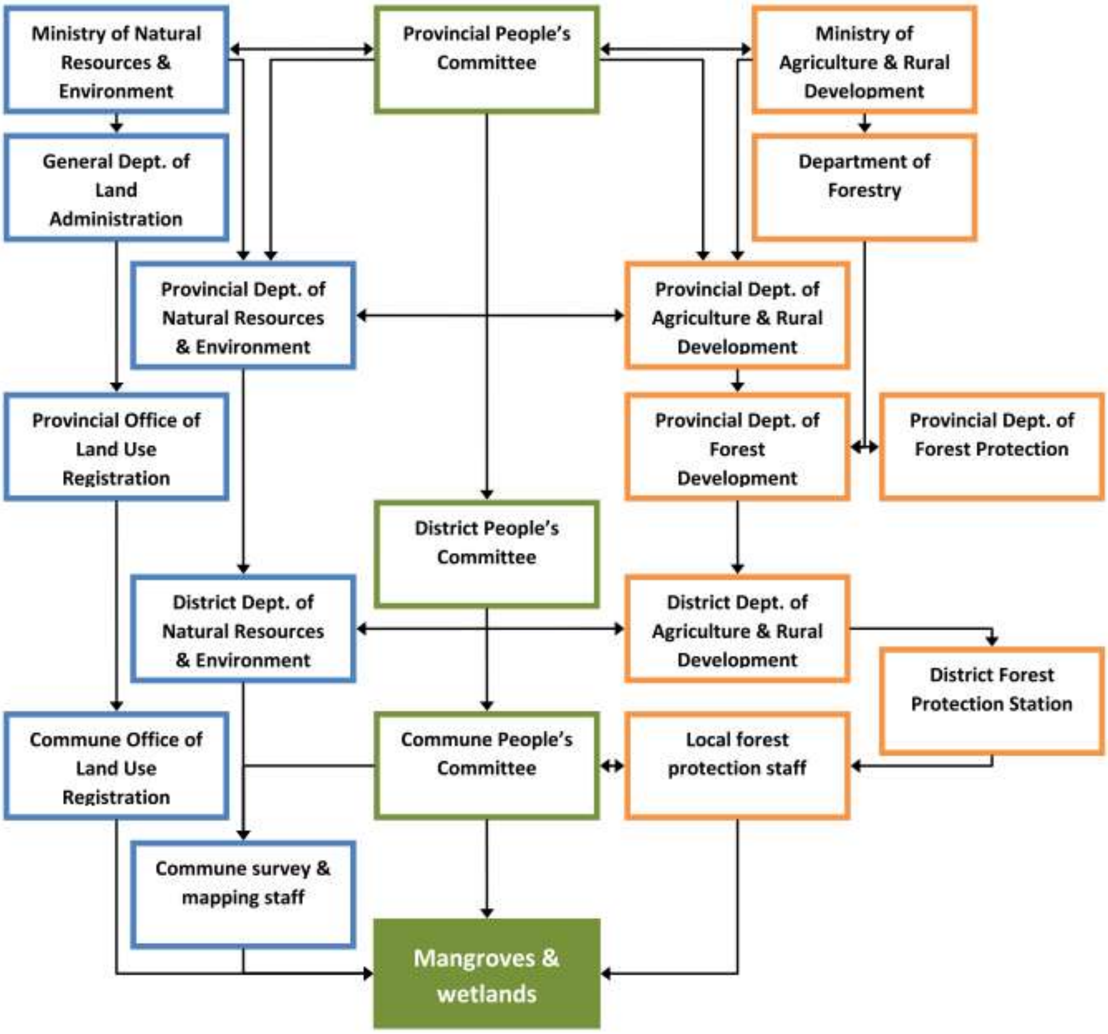

Figure 2 Mangrove management jurisdictional system in Vietnam (adapted from Hawkins et al., 2010)

1.4. Legal instruments for mangrove forest management

A paper by Pham (et al., 2019) discussed different documents regarding mangrove management in Vietnam, ranging from documentation, journal articles and reports, to statistics (national and provincial), policies (strategies, Decrees, circulars, and Decisions), and documents from donors and civil organisations. Laws are the highest form of legal documents in Vietnam, and they provide the overall legal framework for managing and protecting mangrove forests. Policies are specific plans and guidelines based on the Laws' provisions, providing more detailed information on how to implement the Laws. Circulars are specific instructions or guidance documents issued by government agencies to provide more detailed information on how to implement policies and Laws. Decisions, on the other hand, pertain to specific actions by government agencies or local authorities to manage and protect mangrove forests. These Decisions are based on policies, circulars, and Laws, and they are intended to implement the specific provisions of these documents. Together, these legal documents provide a comprehensive framework for managing, protecting, and conserving mangrove forests in Vietnam. In addition, they should ensure that government agencies, local authorities, and other stakeholders clearly understand their roles and responsibilities in managing and protecting the mangrove ecosystems.

The sections below outline the development of the jurisdiction regarding mangrove forest management, and the most important legal instruments are explained. For further, in-depth information and context on the legal instruments and their content, the reader is referred to Chapter 2. It is important to note, that when Laws are enacted or amended, they often come with Decisions and Decrees that help clarify how the Law should be interpreted and implemented. However, over time, the accumulation of Laws, Decisions, and Decrees can create a complex web of regulations that is difficult to navigate. Confusion is created by the use of repealed Laws in legislation in force. A lack of clarity causes difficulties in correctly interpreting and applying the current legislation. This exacerbates the wickedness of the problem by creating confusion, delays, conflicting approaches, and accountability issues. This highlights the need for clear lines of responsibility and communication between agencies to effectively tackle wicked problems.

1.4.1. Forest access versus property

This research distinguishes between land (land allocation, tenure) and people (access, use-rights, decision-making) actively involved in the decision-making processes in mangrove-shrimp farming communities. Land tenure refers to the legal terms (rights and obligations of the holders) on which property is held. Access is defined as the ability to benefit from mangrove-shrimp farming. Access is closely related to property. However, benefitting from mangrove-shrimp farming is not implicit when having only property rights. Often *de jure* and *de facto* rights are used to distinguish between the two. Property refers to *de jure* rights. Access is broader, referring to *de jure* and *de facto*[4] rights (Ha, 2012a; Tan, 2005). People are more likely to participate in forest activities when they have more benefits (thus access) from forests (Ha et al., 2012b). Since 2008, farmers have been granted *de facto* rights and can now enjoy access to their forest land and ponds while still being entitled to a share of the benefits from the mangrove forest (Ha, 2012a).

1.4.2. Mangrove forest jurisdiction

After the proclamation of the Democratic Republic of Vietnam in 1945, Vietnam implemented a central planning system for forest management. Forests were the people's property and must be administered by the State (Dang, 2022). State forestry enterprises[5] were responsible for all forest-related operations (Ha et al., 2012a). These first legal instruments mostly decentralised the responsibility for forests by providing communities with use rights instead of the actual devolution of mangrove management (ownership) to local users; forest-related operations were handed to state forest enterprises (Ha et al., 2014). State ownership of forest resources led to *de jure* state property but *de facto* open access (Ha et al., 2012b). The issue regarding forest benefits defines the fragility of the jurisdictional system in mangrove management. Local needs were unmet, and illegal logging increased due to open forest access and increasing demand for shrimp farming (Liu et al., 2020). The Doi Moi movement was launched in 1980, which allocated forest and forest management to different entities. This marked the beginning of the actual forest management devolution in Vietnam, and in 1983 the State officially began allocating forestlands to households, communes, cooperatives, and Forest Management Boards (Dang, 2022).

The 1993 Vietnamese Land Law (24-L/CTN[6]) stipulated that forest management was transferred from state forest enterprises to households, villages, and communes for sustainable and long-term use (red book[7]). Forestland was not transferable (Ha, 2012b). The evaluation and approval of land and forest conversion plans are the responsibility of Provincial People's Committees for organisations and District People's

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[5] Since 2006 State Forest Enterprises have changed to State-Owned Forest Companies (Forest Companies), where the companies post their own business independently.
[6] Luật đất đai [Land Law] No. 24-L/CTN (Jul. 14, 1993)
[7] Red (book) certificates give farmers land use rights for 50 years, and freedom to use the land as they see fit (Ha et al., 2014)

Committees for households and individuals (MONRE, 2013). Conversion plans must comply with the relevant land use master plan and forest protection and development strategy and require the completion of an environmental impact assessment for forest land clearance. The commune People's Committee exercises the State's authority over land at the commune level. However, due to their limited resources and expertise, effective mangrove management by commune People's Committees is often lacking, resulting to open access areas under their control (Hawkins et al., 2010).

In 1995, Decree 01/CP[8] allowed state forest enterprises to contract with households to plant and protect forests for up to 20 years or one production cycle. These green[9] books hold rights and conditions that directly affect the benefits they receive from forest conservation and use. However, these tenure rights are fuzzy due to spontaneous immigration and informal rights transfer (Ha et al., 2014; Ha, 2012a). In 1998, the Vietnamese government distributed 7.2 million hectares of forestland to households, communes, and cooperatives, but state entities and forest management boards got the majority of 5.4 million hectares. After 2000, reforesting and afforestation of mangroves increased with a focus on innovation, better management, and improving quality and reliability (Ha, 2012b).

Concerns over management effectiveness and equitability of the red and green book contracts led to the release of a National Benefit-Sharing Policy under Decision 178/QD-TTg [10] by the Vietnamese Government in 2001 (Ha et al., 2012a). This Decision is one of Vietnam's most essential legislations on mangrove management in shrimp farming (further explained in Section 5.1). The State remains responsible for land use planning. However, grants use rights to individuals or entities through direct land allocation or allocation to a State body that contracts with third parties (Hawkins et al., 2010). The Vietnamese Prime Minister authorised the DARD in the Mekong Delta of Vietnam to allocate protected mangroves to local communities for protection and livelihood improvement under contracts (Luom et al., 2021). Households and individuals can now be assigned forests and forest lands or leased and be funded by the state for managing, protecting, and zoning off forests for regeneration according to current regulations. Alternatively, being contracted by State organisations (like forest companies) to protect, zone off for regeneration, and plant forests.

1.4.3. Mangrove forest management zones

In recent years, Vietnam has prioritised mangrove protection and renewal, leading to the revision of the Law on Forest Protection and Development (25/2004/L-CTN[11]). This Law categorises all forest types into three types: special-use, protection, and production forests (Ha, 2015; Peoples Committee, 2019), each with its complex forest management policy and use mechanisms (Thang, 2015). The special-use forests are designated for flora and fauna conservation, including national parks, and timber extraction is only allowed in specific cases. The protection forest is established to protect the environment through climate regulation, restriction of natural calamities, and erosion prevention, focusing on soil health and the natural environment. Furthermore, the production forest is used for producing and trading timber and non-timber forest products (Vo et al., 2015). Production forest owners must develop plans and guidelines for sustainable

[8] Nghị định ban hành bản quy định giao khoán đất sử dụng vào mục đích sản xuất nông nghiệp, lâm nghiệp, nuôi trồng thuỷ sản trong các doanh nghiệp Nhà nước [Decree on the government's issuing provisions on allocation of land for agricultural production, forestry and agricultural products in state-owned enterprises] No. 01-CP (Jan. 4, 1995)

[9] 'Green book' forestland use titles grant the households the same rights as the red book title, with a different set of conditions concerning the time of the harvest and benefit sharing mechanism applied by state forestry companies and management boards (Ha et al., 2012a)

[10] Quyết định về quyền hưởng lợi, nghĩa vụ của hộ gia đình, cá nhân được giao, được thuê, nhận khoán rừng và đất lâm nghiệp Hien [Decision on the benefits and obligations of households and individuals assigned, leased or contracted, No. 178/QD-TTg (Nov. 12, 2001)

[11] Luật bảo vệ và phát triển rừng [Law on forest protection and development], No. 25/L-CTN (Dec. 14, 2004)

forest management under the Ministry of Agriculture and Rural Development (MARD). These guidelines must be submitted for approval to the DARD (Jhaveri et al., 2018).

In 1999 Decision 116/QD-TTg[12] was released to protect coastal safety in coastal Provinces (including Ca Mau) by planning zoning areas; full protection zone, buffer zone, and economic zone. The forest categories described above (special-use, production, protection) fall within these zones. In these zones as defined by Decision 116, the presidents of the People's Committee of the Provinces oversee the monitoring and management of mangroves (Tan, 1999). The full (or vital) protection zone is a 100 to 500-meter-wide strip along the western coast where no settlements are allowed (Tran et al., 2015). In the (less vital) buffer zone, which is five hundred meters to four kilometres land inwards from the full protection zone, settlement is allowed (Vo et al., 2015). A ratio for mangrove to aquaculture of 60:40 should be followed (Christensen et al., 2008) (note the use of 'ratio'). In the economic zone, settlement is allowed (Ha et al., 2014; Vo et al., 2015). Mangrove-shrimp farms are generally in the buffer zone, and extensive shrimp farms are in the economic zone. Full protection and buffer zones are under the management of Forest Companies, and they are tasked with reforestation, thinning, harvesting and allocating forest to households. Farmers in the buffer zone can obtain a 20-year lease (green certificate). In economic zones, land tenure and red certificates are released to owners for long-term land use rights (red certificate) (Ha, 2012b). Households and forestry companies in Vietnam can be granted long-term use rights to production and less restricted protection forests through a "red book," which includes a bundle of rights such as use, transfer, lease, inheritance, and mortgage. Leasing forests is also possible but has been implemented slowly due to low economic returns from forestry. As Vietnam has no private ownership of land or forestland, these allocation conditions apply to households and forestry companies (Ha et al., 2012b).

Specific zones within the special-use forest can be created, such as; core/strictly protected zones, ecological rehabilitation zones, administration and service zones, landscape-protected areas, and buffer zones (Jhaveri et al., 2018). Different management styles pertain to these zones depending on their specific purpose. For example, ecological rehabilitation zones may involve a combination of natural regeneration and cultivation of native species, while strictly protected zones focus solely on conservation. On the other hand, buffer zones aim to support sustainable socio-economic development and livelihoods while preventing encroachment into higher protection status zones (Jhaveri et al., 2018). People in the protection forests within the full protection zone are allowed to collect dead timber products, and shrimp cultivation is not allowed. These forest categories and zoning areas should aid the conservation and protection of mangroves. However, this is not always the case, as there are still some highly intensive shrimp farms in areas where mangroves should be legally conserved (Hawkins et al., 2010; McEwin & McNally, 2014; Tan, 2005). As the Environemental Justice Foundation stipulates; logging of mangrove trees for firewood is illegal, but the Law is reportedly circumvented by allowing logs to dry in situ (EJF, 2003). The complexity of, and overlap within, the jurisdictional system have inadvertently contributed to an increasing loss of mangroves (Pham et al., 2019).

1.4.4. Organic shrimp cultivation through eco-certification

In 2008 the market price of shrimp decreased immensely due to the Global Financial Crisis that resulted in unstable markets and overproduction resulting from increasing numbers of actors in the market chain. To cope with these market changes, increasing transitions occurred to intensive shrimp farming, salt

[12] Quyết định của thủ tướng chính phủ về việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

production, or fish farming (Ha et al., 2013). Intensive shrimp farming led to the degradation of mangrove forests, regardless of the pertinent legal protection. To respond to fLawed institutional structures (Ha et al., 2012a), private approaches for organic shrimp cultivation have been proposed as promising alternatives (Baumgartner & Nguyen, 2017).

Due to the mangrove deforestation, major shrimp producers expressed interest in the organic shrimp certification program introduced by the Vietnam Association of Seafood Exporters and Producers in the early 2000s. Ca Mau Frozen Seafood Processing Import-Export Corporation created momentum behind organic shrimp farming principles, which require a 50 percent mangrove cover (note the use of 'mangrove cover') in shrimp production ponds. Organic shrimp sells for 25 to 30 % more than conventional shrimp. Nam Can Sea Products Import Export Joint Stock Company joined the organic shrimp movement in 2008. Due to low input requirements, farmers were able – in theory – to adopt organic shrimp farming and its certification. However, as only a 20% price premium was given instead of 25-30%, only a small proportion of farmers did apply for eco-certification (Jhaveri et al., 2018). However many farmers exactly have applied for eco-certification after this publication of 2018, remains uncertain.

Producers must follow the certification standards, of which a specific ratio of mangrove-to-pond is most important (McEwin & McNally, 2014; Nguyen et al., 2022). When a shrimp farm meets the certification standards, certification can be obtained (this process is voluntary), guaranteeing the operations' sustainability. A 'sustainable operation' means that a shrimp farm has a reduced disease risk, higher quality production of shrimps, and no artificial stock or feed is used (Baumgartner & Nguyen, 2017). As more consumers prefer environmentally friendly products, their willingness increases to pay higher prices. Global customers and companies are now willing to pay a premium price of 20% to 50% extra for sustainable, hygienic, environmentally friendly aquaculture products, according to Stichting Nederlandse Vrijwilligers (SNV, 2015). This creates a financial incentive for farmers to adopt and invest in this certified organic shrimp farming model (SNV, 2015; Tran et al., 2015). Additional income could be generated by diversifying their livelihoods by participating in other off-farm activities, such as middlemen, growing and/or selling groceries, or raising livestock (Ha et al., 2013).

Asides from Naturland, many other third-party eco-certification practices have been introduced, such as; Global Good Aquaculture Practice, Aquaculture Stewardship Council, Naturland Fair, Certified Naturally Grown, Certified Organic Aquaculture, Best Aquaculture Practices, Better Management Practice and Good Aquaculture Practice. Integrated shrimp farms protect biodiversity more than other shrimp farming systems. However, despite the benefits of these integrated systems, their uptake has been slow (Nguyen et al., 2018). The exact contributions of integrated shrimp farming systems to biodiversity remain underdeveloped.

Only 10 percent of global farmed shrimp production was certified at the end of 2019, despite eco-certification programs being in operation for over 20 years (Ha, 2012a). However, aquaculture must be more sustainable in protecting the mangroves (Ahmed et al., 2017; Veettil et al., 2019). Farmers should benefit from the Payment for Ecosystem Services (see below), however mangroves are decreasing eventhough the Law limits the exploitation of mangroves in production forests (Baumgartner & Nguyen, 2017).

To increase the interest in participating in eco-certification, the IUCN and the Dutch SNV have implemented the Mangroves and Markets project (SNV, 2020). The International Climate Initiative funds this project and supports owners of small shrimp farms in Vietnam to meet the requirements of organic certification of their shrimp farms, e.g. Naturland and other organic labels. This project aims to restore mangroves in Ca Mau, Tra Vinh and Ben Tre Provinces. To increase the interest in participating, the project developed a Payment for Ecosystem Services (PES) mechanism, paying farmers based on the size of their certified farming area (SNV, 2015). A big seafood company (ranked 50th among the top one hundred of the world), Minh Phu, partnered with the project from 2013 to 2020; organic shrimp are produced in mangrove-shrimp farming practices certified to Naturland's standards. Naturland certification was successful for over ten years in Nam Can District, which lies within Ca Mau Province. According to the Naturland Certification, households should have 50% mangrove cover on their farms and receive 500.000 Vietnamese Dong (VND) (19.48 Euros) per year for each ha of mangrove forests in their shrimp pond (Naturland, 2022; Le, 2021). It is important to note that the percentage of mangroves on-farm, refers to the mangrove coverage on-farm level and not to the policy zone level. Each farm parcel, delineated by its respective boundaries, should encompass e.g. 50% mangroves (according to Naturland standards). However, it remains uncertain whether multiple land parcels owned by a single entity can merge their boundaries and decide where to plant mangroves. Land versus forest tenure is a complex situation in Vietnam, as explained above.

Naturland’s standard stipulated that mangroves need to be protected and may not be removed to expand shrimp farms or ponds for shrimp. Shrimp farms in mangrove areas with less than 50% coverage should reforest to comply with this standard within five years and provide documentation and plans (Baumgartner et al., 2017). The Vietnamese Government aims to create an organic coast by implementing (Naturland) eco-certification for all mangrove-shrimp farming practices in Ca Mau Province (Ha et al. 2012). This organic coast project demonstrates how shrimp production revenues can support mangrove conservation through a Payment of Ecosystem Services (PES) mechanism, through partnerships between small-scale shrimp farmers, a major shrimp company, and the government through eco-certification (Jhaveri et al., 2018).

1.4.5. Payment of Ecosystem Services: PES, PFES, REDD+

The role of ecosystem services in natural resource management policies has recently gotten more attention as it offers increased protection of biodiversity and conservation, integrated natural resource management, and promoting sustainable forest management (Ahammad et al., 2021). The Vietnamese Government has been focusing increasingly on ecosystem services by developing legislation to fund mangrove protection and restoration. This is done to create incentives for participation, including Payments for Forest Environmental Services (PFES) and Reducing Emissions from Deforestation and Forest Degradation (REDD+) (Thuy et al., 2021), as explained in the sections below.

PFES is based on Payments of Ecosystem Services (PES) and is designed to create incentives for individuals, households, and communities to protect environmental services by funding their related management practices. Ecosystem services are converted to revenue streams (Talberth, 2015). PFES is the branch of PES that focuses specifically on forests. In 2004, the government of Vietnam created the basis for a nationwide program called PFES; back then, it was not yet called PFES (Ngoc et al., 2021). In 2010, the government released a National wide Decision (No. 99/2010/ND-CP[13]) outlining the principle of PFES policy, stating that organisations and individuals who benefit from forest environmental services must pay forest owners for the services provided (Ha, 2015). This Decree permits individuals, groups, or organizations to use their

[13] Nghị định về chính sách chi trả dịch vụ môi trường rừng [Decree on payment policy for forest environment services] No. 99/ND-CP (Sep. 24, 2010)

own funds to reforest areas. An area can be qualified for PFES payments if it meets the forest criteria specified in Circular[14] No. 34/2009/TT-BNNPTNT[15].

According to research by Pham (et al.) up to 2013, high reforestation and afforestation costs, in combinations with low PFES returns discouraged people from (re-)planting mangroves (Pham et al., 2013). Since 2010, over 20 legal documents have been released at different levels on the implementation guidelines of PFES (Ngoc et al., 2021). PFES goals are to improve forest quality and quantity, increase the forestry sector's contribution to the national economy, reduce the state's financial burden for forest protection and management, and improve social well-being (Pham et al., 2013). PFES schemes are subsidised by different institutions, such as government funds, private foundations, or funds of large-scale projects of environmental NGOs, tourist fees (entry prices for site access), taxes, e.g. As many forests in Vietnam are off limits for intensive uses (like in the protection and special-use zones), ecosystem service valuation methods play a significant role in this protection. Ecosystem service valuation methods are used to quantify ecosystem and their services and are the basis for PES and PFES schemes (Talberth, 2015). The payments depend on the area managed and are determined by forest management zone (protection forests, special-use forests, production forests), forest status (rich, medium, poor, restoration forest), and forest history (natural forest, plantation). The Provincial People's Committees determine these factors. Additional management costs are subtracted (Pham et al., 2012).

Mangroves can also be eligible for REDD+, which is a performance-based scheme. It is part of The National Action Program: '*Reduction of greenhouse gas emissions through efforts to reduce deforestation and forest degradation, sustainable management of forest resources, conservation and enhancement of forest carbon stocks'* (Hai et al., 2020; Nguyen et al., 2022). It is designed to demonstrate Vietnam's sincerity and resolute commitment to participate successfully in the global effort to safeguard the Earth's climate system (Hai et al., 2020). REDD+ can stimulate national payments for environmental services whilst reducing national poverty (Ngo et al., 2020; Pham et al., 2012). In Vietnam, payment can be from international buyers under the REDD+ scheme; or domestic buyers under the Payment for Forest Ecosystem Services (PFES) scheme of the Vietnamese Government (Pham et al., 2012).

1.5. Research gap and scientific relevance

The integration of mangroves in shrimp farming practices has been put forward as a way to restore mangroves whilst continuing shrimp production in Vietnam; however, its uptake has been slow. Effective implementation of sustainable mangrove-shrimp farms (through eco-certification, PFES and REDD+ mechanisms) should provide the necessary means for mangrove conservation in the forest management zones in Vietnam (Ahmed et al., 2017; Veettil et al., 2019). If Vietnam succeeds in developing sustainable aquaculture, then there will be significant global impacts on the urgent need for mangrove forest protection to prevent coastal erosion and mitigate climate change (Xuan et al., 2021).

Much research has been performed to aid successful mangrove restoration through its implementation on shrimp farms. Research has brought attention to stakeholder perception (Xuan et al., 2021), climate effects on shrimp farming practices (Di Giusto et al., 2021; Ellison, 2015; Peoples Committee, 2019; Quach et al., 2015, 2017; Quach, 2018; Talberth, 2015) and policy implementation impacts (Dang, 2022; Ha et al., 2014;

[14] These criteria include slow- and fast-growing trees with a height greater than 1.5 and 3 meters, respectively, with 1000 trees per hectare and five live trees in each 20-meter plot.

[15] Thông tư quy định tiêu chí xác định và phân loại rừng [Circular on criteria for forest identification and classification] No. 34/TT-BNNPTNT (Jun. 10, 2009)

Nguyen et al., 2017; Rametsteiner, 2017). Several measures have been taken to increase incentives for shrimp farmers to adopt sustainable shrimp farming techniques, such as economic benefits (like PFES and REDD+). These studies collectively contribute to advancing the understanding of mangrove restoration on shrimp farms in Vietnam and the importance of effective top-down management. However, its implementation through forest management zones remains undiscovered.

To restore mangrove ecosystems, which aligns with the National Action Plan of Vietnam, spatiotemporal mangrove change mapping is critical to support the subsequent land-use planning and restoration of mangrove ecosystems (Son et al., 2015). This can help policymakers and stakeholders evaluate the effectiveness of existing policies and identify areas where new policies are needed. Mangrove mapping and change detection of mangrove forests in Ca Mau has been done in previous years using different techniques, e.g. 1979 to 2013 using Landsat data and object-based image analysis (Son et al., 2015), 2004-2013 using multi-temporal SPOT satellite imagery (Hauser et al., 2017). Changes in shrimp farming practices can also drive policy changes because of the potential for significant environmental and social impacts. As stakeholders become more aware of these impacts, they may demand and advocate for changes (in mangrove cover) that can ultimately influence industry policies and regulations. Moreover, change detection of mangroves using remote sensing techniques in different forest management zones (production, protection, special use) in Vietnam can help effective conservation and management strategies. The application of remote sensing techniques to detect changes in mangrove ecosystems in production and protection forests in Vietnam holds promise for informing conservation and management strategies. By tracking alterations in the distribution and extent of mangrove forests within these forest management zones, more effective policies can be developed to address the unique challenges associated with each. To help policymakers create effective legislation regarding aquacultural strategies, the gap between current legal instruments and farmers' perceptions should be determined (Xuan et al., 2021).

1.6. Mangrove-shrimp farming as a wicked problem

Shrimp farming is currently a major income source in Vietnam, and the global food demand is high. However, shrimp farming management should be weighed against the ecological impacts it causes. For example, local communities may depend on the forests in the production zones for their livelihood and cultural practices, whilst the Vietnamese Government might prioritise larger-scale economic development in the production zones. Moreover, conservation organisations may advocate for the protection of forest ecosystems and prioritise special-use forest monitoring. The legal framework of mangrove forest management in Vietnam is complex and overlapping in tenure, making it challenging for shrimp farmers to implement sustainable mangrove-shrimp practices. Illegal logging remains a considerable problem, weakening the effort to implement sustainable forest management. Logging, in turn, causes significant climate influences by extreme carbon exhaustion. Shrimp farming can have social impacts, such as conflicts over land use. High-pressure working conditions often characterise the shrimp farming industry. Given these factors, implementing the different forest management zones in this complex legal framework in Vietnam, this problem is multi-faceted and wicked (Georgiadou & Reckien, 2018). The restoration of mangroves is a complex undertaking that requires aligning political, social, economic, and biophysical conditions (Thuy et al., 2022). It requires multiple perspectives to find common ground to formulate a solution to make the problem less wicked. Sustainable forest management should balance the different mangrove forest management zones' economic, ecological, and social benefits while protecting the ecosystem for future generations.

Wicked problems are characterised by the degree of knowledge and the degree of consensus between stakeholders' policy goals and values. Mangrove implementation on shrimp farms is defined by high ecological complexity, as mangroves contribute significantly to coastal ecosystems. The different mangrove forest management zones all have specific ecological characteristics and functions and are each managed differently. Balancing these functions with sustainable forest management through, e.g., eco-certification can be challenging. Wicked problems are characterized by unpredictability, ambiguity, conflicting stakeholder interests, and the involvement of multiple policy jurisdictions (Simon, 2016).

1. **Degree of knowledge:** Extensive research has been conducted on the present state of mangroves worldwide and in Vietnam, revealing the importance of mangroves and the viability of integrated mangrove-shrimp farming. However, research is still required to evaluate the effectiveness of implementing different mangrove forest management zones. Stakeholders have limited knowledge regarding current policies due to differing perspectives and priorities, while the policies themselves are intricate, involving legislation out of force and overlapping. These factors confuse farmers in implementing accurate measures for mangrove preservation, revealing the limited knowledge of top-down regimes in executing policies. These elements collectively contribute to the wickedness of the problem.

2. **Degree of consensus:** The issue of mangrove conservation and management in Vietnam is inherently wicked due to the lack of consensus among stakeholders. Conflicting values and goals stemming from different pressures on production and ecosystem restoration cause stakeholders to prioritize their interests. As a result, there is a limited degree of consensus on implementing policies and measures to conserve and restore mangroves effectively. This lack of consensus leads to confusion and inconsistencies in implementing policies, hindering progress towards effectively managing and conserving mangroves.

This research aims to move the problem from (4) wicked or unstructured problems to (3) moderately structured problems by increasing the knowledge of the effectiveness of forest management use types and zoning areas, see Table 2 below.

Table 2 Wicked problem framework (adapted from Georgiadou & Reckien, 2018)

		Policy goals and values among stakeholders	
		Consensus	Dissensus
Knowledge on problem	Certain	(1) Tame or structured problems *Geo-information tools as a problem solver*	(3) Moderately structured problems *Geo-information tools as mediators*
	Uncertain	(2) Moderately structured problems *Geo-information tools as analyst and/or advocate*	(4) Wicked or unstructured problems *Geo-information tools as problem recogniser*

The effectiveness of policy implementation in the forest management zones

1.7. Research problem

The conservation and management of mangroves in Vietnam is a wicked problem that involves complex and interrelated challenges. One of the challenges is the implementation of policies to manage and preserve mangroves, which requires addressing issues such as overlapping policies, complex management structures, and uncertainty in requirements. Understanding the relationship between these policies, shrimp farming practices, and mangrove change detection in different forest management zones is possibly insightful for developing effective conservation and management strategies for sustainability and carbon storage goals. To address these challenges, this research examines policy management within mangrove forest zoning areas (production, protection), assesses mangrove change or stagnation per zoning area, and explores farmers' perspectives and opinions on mangrove management. The research will employ spatiotemporal mangrove change mapping within these zones. By doing so, this research seeks to support subsequent land-use planning and restoration of mangrove ecosystems in Ca Mau, aligning with Vietnam's National Action Plan. The wickedness in this research stems from the complex and interconnected challenges facing mangrove conservation and management in Vietnam, which require innovative and interdisciplinary approaches to address effectively.

1.7.1. Research objectives and questions

The main objective of this research is to analyse the relationship between policy implementation, farmers' perspectives and change detection of mangroves in different zoning areas (production, protection) to understand and inform effective conservation and management strategies in Vietnam. The research objectives (RO) and questions are formulated below:

RO1: To determine the differences and similarities between mangrove forest-related legal instruments related to mangrove cover in the different forest management zones in Ca Mau

RQ1.a: What are the legal instruments enacted for mangrove cover management in the different forest management zones in Ca Mau?

RQ1.b: What is the current monitoring system for mangrove cover management in the different forest management zones in Ca Mau?

RO2: To analyse the difference between the forest management zones in their mean mangrove cover on-farm in Nam Can District 2011 versus 2019

RQ2.a What was the mean % coverage of mangroves on-farm per forest management zone in the study area (2011)?

RQ2.b What was the mean % coverage of mangroves on-farm per forest management zone in the study area (2019)?

RQ2.c What is the mean % change in mangrove cover on-farm per forest management zone in the study area, and how do these differ between the different forest management zones?

RQ2.d How did the different land cover types change over time (2011-2019)?

RO3: To assess whether the remote sensing-based manually delineated mangrove cover on-farm are in line with farmers' estimates or other forest policies related to mangrove cover in the different forest management zones

- **RQ3.a** Is there a statistically significant difference between the averages of the estimated mangrove cover on-farm and the delineated mangrove cover on-farm in 2011 in Nam Can?
- **RQ3.b** Is there a statistically significant correlation between farm size and mangrove cover (change) on-farm in Nam Can?
- **RQ3.c** Is there a statistically significant correlation between distance to open water and mangrove cover on-farm in Ca Mau?

RO4: To analyse the motives of shrimp farmers in different forest management zones to maintain or change their mangrove cover on-farm in Nam Can District and Ca Mau Province

- **RQ4.a** To what extent is there a difference between the forest management zones in whether farmers care about mangroves on the level of Ca Mau Province and Nam Can District?

- **RQ4.b** To what extent is there a difference between the forest management zones in the benefits for farmers in mangrove exploitation and aquaculture, on the level of Ca Mau Province and Nam Can District?
- **RQ4.c** To what extent is there a difference between the forest management zones in farmers' beliefs regarding the legality of mangrove logging for construction wood, on the level of Ca Mau Province and Nam Can District?
- **RQ4.d** To what extent is there a difference between the forest management zones in farmers' beliefs regarding the legality of mangrove logging for fuel wood, on the level of Ca Mau Province and Nam Can District?

2. POLICY FRAMEWORK

Table 3 below provides an extensive overview of the legal instruments (1961 till 2022) on mangrove management in shrimp farms on the national level (red) and on the provincial level of Ca Mau (blue). Their publishing date (often enacted within two weeks) and whether they are currently[16] still in force are included. The justification for choosing Ca Mau as the study area is described in Chapter 3.

Table 3 Legal instruments on National Level and Ca Mau Province level

Legal Instrument	Publishing date	In force	Description
Decree 15 CT/CTCW	10/03/1961	No	Forests are the people's property and must be administered by the State (Dang, 2022).
Decision 57/QD.UB	06/03/1985	No	Farmers must cover at least 80% of the mangroves and 20% for pond aquaculture. Mangroves must be planted at a density of 20,000 trees/ha.
Decision 389/QD.UB	08/11/1988	No	Contains temporary regulations on allocating mangrove land to households for production and protection. Requires farms to have an 80:20 mangrove-to-pond ratio with a tree density of 20.000 trees/ha (Ha et al., 2014).
Decision 64/QD.UB	18/03/1991	Yes	Repeals 389/QD.UB; farmers must maintain at least 80% mangrove cover on their farms if they have less than 20 ha of mangrove forest or 10 ha of empty mangrove. Renewable land-use rights are granted for 20 years to individual households under contract with forest state enterprises (Ha et al., 2014).
Law 58 LCT/HDNN8[17]	12/09/1991	No	Forest Resources Protection and Development Law facilitates further forest devolution (Dang, 2022; Trieu et al., 2020).
Law 24-L/CTN[18]	14/07/1993	No	Land Law. Stipulates that forest management is transferred from state forest enterprises to households, villages, and communes for sustainable and long-term use (red book). Forestland is not transferable.
Decree 01/CP[19]	04/01/1995	No	The government allows State Forest Enterprises to contract with households for up to 20 years (or one production cycle) to plant and protect forests. These contracts are called green book certificates and come with specific rights and conditions impacting the benefits of forest conservation and use (Ha, 2012a). Repealed by Decision 135/ND-CP.
Decision 116/QD-TTg[20]	05/05/1999	Yes	Implements planning zoning areas to protect coastal Provinces (including Ca Mau); full protection zone, buffer zone, and economic zone (Tan, 1999).
Decree 163/ND-CP[21]	16/11/1999	Yes	Leasing forest is now possible. Allocation and leasing conditions apply to households and forestry companies that are granted forestland or forestry contracts.(Ha et al., 2012a).
Decision 08/QD-TTg [22]	11/01/2001	No	Issues the regulation on the management of special-use forests, protection forests and production forests, which are natural forests (Tan, 2005)

[16] As of April 2023

[17] Luật bảo vệ và phát triển rừngcủa quốc hội [Law on forest protection and development of the national assembly] No. 58-LCT/HDNN8 (Aug. 12, 1991)

[18] Luật đất đai [Land Law] No. 24-L/CTN (Jul. 14, 1993)

[19] Nghị định ban hành bản quy định giao khoán đất sử dụng vào mục đích sản xuất nông nghiệp, lâm nghiệp, nuôi trồng thuỷ sản trong các doanh nghiệp Nhà nước [Decree on the government's issuing provisions on allocation of land for agricultural production, forestry and agricultural products in state-owned enterprises] No. 01-CP (Jan. 4, 1995)

[20] Quyết định của thủ tướng chính phủ về việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

[21] Nghị định của chính phủ về giao đất, cho thuê đất lâm nghiệp cho tổ chức, hộ gia đình và cá nhân sử dụng ổn định, lâu dài vào mục đích lâm nghiệp [Decree of the Government: On allocation and lease of forestry land to organizations, households and individuals for stable and long-term use for forestry purposes] No. 163/ND-CP (Nov. 16, 1999)

[22] Quyết định của thủ tướng chính phủ về việc ban hành quy chế quản lý rừng đặc dụng, rừng phòng hộ, rừng sản xuất là rừng tự nhiên [Decision of the prime minister on the promulgation of regulations for management of special-use forest, protection forest and production forest as natural forest] No. 08/QD-TTg (Jan. 11, 2001)

Table 3 (continued)

Legal Instrument	Publishing date	In force	Description
Decision 178/QD-TTg [23]	12/11/2001	Yes	'National Benefit-Sharing Policy'; The State remains responsible for land use planning. However, grants use rights to individuals or entities through direct land allocation or allocation to a State body that contracts with third parties (Hawkins et al., 2010).
Decision 24/QD-UB	01/02/2002	No	This Decision reforms Ca Mau's forest and forestry management. It converts use-right contracts to red certificates and allows farmers to benefit from timber marketing and pond dredging. The policy mandates a 70% coverage of mangroves in the area, but for households, it varies depending on the total farm area (Baumgartner et al., 2016; Jhaveri et al., 2018).
Law 17/QH11[24]	26/11/2003	No	Law on Fisheries. Contains all management regulations related to aquaculture and mariculture, ecosystem preservation, and protection of fish and the environment.
Land Law 13/QH11[25]	26/11/2003	No	Repeals Vietnamese Land Law 1993. This Law prescribes land management and use.
Directive 05/CT-TTg[26]	09/02/2004	Yes	Directive on the organisation and implementation of the Land Law (13/QH11) with special regard to land management and the rational use and exploitation of land resources.
Law 25/L-CTN[27]	14/12/2004	Yes	Forest Protection and Development Law (FPDL). Repeals Law 58 LCT/HDNN8 (1991). The FPDL categorises forests into three categories: special-use, protection, and production.
Decision 135/ND-CP[28]	08/11/2005	No	Decree on the allocation of agricultural land, production forest land and land with water surface for aquaculture in state-owned farms and state-owned forestry farms
Law 52/QH11[29]	29/11/2005	No	Law on Environmental Protection. Provides information on activities, policies, measures and resources for environmental protection and rights and obligations of organisations and individuals in environmental protection.
Directive 38/CT-TTg[30]	05/12/2005	Yes	Implements FPDL 2004. Mandates a resurvey and replanning of protection, special-use, and production forests, with the Ministry of Agriculture and Rural Development responsible for national reserve forests. A working group oversees the process and reports any issues to relevant agencies and the Prime Minister.
Decree 23/ND-CP[31]	03/03/2006	No	Implements FPDL 2004. The Decree outlines measures for forest management, including planning, assigning, leasing, and recognizing forest use-rights, and organizing management and protection. Is amended by 98/2011/ND-CP
Decision 186/QD-TTg[32]	14/08/2006	No	Implements FPDL 2004. Repeals Decision 08/QD-TTg (2001); promulgates the regulation of forest management, allows households and organisations allocated submerged land in both protection and production forests to use up to 40 percent of the area for agriculture or aquaculture activities

[23] Quyết định về quyền hưởng lợi, nghĩa vụ của hộ gia đình, cá nhân được giao, được thuê, nhận khoán rừng và đất lâm nghiệp Hien [Decision on the benefits and obligations of households and individuals assigned, leased or contracted] No. 178/QD-TTg (Nov. 12, 2001)
[24] Luật Thủy sản [Fisheries Law] No. 17/QH11 (Oct. 21, 2003)
[25] Luật đất đai [Land Law] No. 13/QH1 (Nov. 26, 2003)
[26] Chỉ thị về việc triển khai thi hành luật đất đai năm 2003 [Directive on organizing the implementation of the 2003 land Law] No. 05/CT-TTg (Feb. 9, 2004)
[27] Luật bảo vệ và phát triển rừng [Law on forest protection and development] No. 25/L-CTN (Dec. 14, 2004)
[28] Nghị định về việc giao khoán đất nông nghiệp, đất rừng sản xuất và đất có mặt nước nuôi trồng thuỷ sản trong các nông trường quốc doanh, lâm trường quốc doanh [Decree on the allocation of agricultural land, production forest land and land with water surface for aquaculture in state-owned farms and state-owned forestry farms] No. 135/ND-CP (Nov. 8, 2005)
[29] Luật bảo vệ môi trường [Law on Environmental Protection] No. 52/QH11 (Feb. 20, 2005)
[30] Chỉ thị về việc rà soát, quy hoạch lại 3 loại rừng (rừng phòng hộ, rừng đặc dụng và rừng sản xuất) [Directive on resurveying and re-planning forests of three kinds (protection forests, special-use forests and production forests)] No. 38/CT-TTg (Dec. 5, 2005)
[31] Nghị định về thi hành luật bảo vệ và phát triển rừng [Decree on implementation of forest protection and development Law] No. 23/ND-CP (Mar. 3, 2006)
[32] Quyết định về việc ban hành quy chế quản lý rừng (Decision on Promulgating the regulation on forest management] No. 186/QD-TTg (Aug. 14, 2006)

Table 3 (continued)

Legal Instrument	Publishing date	In force	Description
Decision 186/QD-TTg[33]	14/08/2006	No	Implements FPDL 2004. Repeals Decision 08/QD-TTg (2001); promulgates the regulation of forest management, allows households and organisations allocated submerged land in both protection and production forests to use up to 40 percent of the area for agriculture or aquaculture activities
Decree 119/NDCP[34]	16/10/2006	Yes	Implements FPDL 2004. Stipulates the organisation and operation of the forest protection service and provides a structure for its organisation.
Decision 18/QD-TTg[35]	05/02/2007	No	The Forestry Development Strategy; proposes solutions for implementing policies and Laws, including developing fee collection mechanisms and creating new financial resources for the forestry sector. The strategy emphasizes shifting the focus from wood exploitation to the protection of forest capital (Dang, 2022; Trieu et al., 2020).
Decree 05/ND-CP[36]	05/08/2008	Yes	The policy aims to mobilize social resources, promote awareness and responsibility for forest protection, and improve forest quality and quantity while reducing the state's financial burden and improving social well-being (Pham et al., 2013).
Circular 34/TT-BNNPTNT[37]	10/06/2009	Yes	Implements FPDL 2004. Provides criteria for identifying and classifying forests for forest survey, inventory and statistics, forest protection and development planning, and forest resource management.
Decision 19/QD-UBND[38]	22/09/2010	Yes	Repeals 24/QD.UB, promulgates several Laws and Decisions (e.g. 135/ND-CP (2005), Land Law (2003), Law on forest protection and development (2004). Farmers must have at least 60% of their farm covered by mangroves.
Decision 99/ND-CP[39]	10/10/2010	Yes	Outlines the PFES policy's principles; organisations and individuals who benefit from forest environmental services must pay forest owners for the services provided.
Decree 98/ND-CP[40]	26/10/2011	Yes	Amends several articles of Decrees on agriculture.
Law 45/QHB[41]	29/11/2013	No	Amends the Land Law of 2003. Prescribes land ownership, powers and responsibilities of the landowner. Is amended by Law 35/2018/QH14.
Decree 43/ND-CP[42]	15/05/2014	No	Implements the Land Law of 2013, detailing a number of articles. Is amended by Decree 136/ND-CP.
Law 55/QH13[43]	23/06/2014	No	Amends Law on Environmental Protection (52/QH11). Establishes the legal framework for environmental protection in Vietnam, including measures to prevent pollution and degradation in mangrove ecosystems (Nguyen & Nguyen, 2022).

[33] Quyết định về việc ban hành quy chế quản lý rừng (Decision on Promulgating the regulation on forest management] No. 186/QD-TTg (Aug. 14, 2006)

[34] Nghị định về tổ chức và hoạt động của kiểm lâm [Decree on the organization and operation of the forest protection service] No. 119/ND-CP (Oct. 16, 2006)

[35] Quyết định phê duyệt chiến lược phát triển lâm nghiệp việt nam giai đoạn 2006 - 2020 [Decision approving Vietnam's forestry development strategy for the period 2006 - 2020] No. 18/QD-TTg (Feb. 5, 2007)

[36] Nghị định quỹ bảo vệ phát triển rừng [Decree on forest protection and development fund] No. 05/ND-CP (Jan. 14, 2008)

[37] Thông tư quy định tiêu chí xác định và phân loại rừng [Circular on criteria for forest identification and classification] No. 34/TT-BNNPTNT (Jun. 10, 2009)

[38] Quyết định ban hành quy định về thực hiện chính sách bảo vệ và phát triển rừng trên địa bàn tỉnh Cà Mau do Ủy ban nhân dân tỉnh Cà Mau ban hành [Decision on the implementation of some forest protection and development policies in Ca Mau Province] No. 19/QD-UB (Sep. 22, 2010)

[39] Nghị định về chính sách chi trả dịch vụ môi trường rừng [Decree on payment policy for forest environment services] No. 99/ND-CP (Sep. 24, 2010)

[40] Nghị định số của Chính phủ: Sửa đổi, bổ sung một số điều của các nghị định về nông nghiệp [Decree on amending and supplementing a number of articles of Decrees on agriculture] No. 98/ND-CP (Oct. 26, 2011)

[41] Luật đất đai [Land Law] No. 45/QHB, (Dec. 9, 2013)

[42] Nghị định quy định chi tiết thi hành một số điều của luật đất đai [Detailing a number of articles of the Land Law] No. 43/ND-CP (May 15, 2014)

[43] Luật bảo vệ môi trường [Law on Environmental Protection] No. 55/QH13 (Jun. 23, 2014)

Table 3 (continued)

Legal Instrument	Publishing date	In force	Description
Decree 19/ND-CP[44]	14/02/2015	No	Implements Law 55/2014/QH13. Amended by Decree No. 136/2018/ND-CP.
Decision 17/QD-TTg[45]	09/06/2015	Yes	Amends Decision 186/QD-TTg of 2006. Prescribes the management, protection, development and use of, and benefits from, protection forests; and protection forest development investment.
Decree 119/ND-CP[46]	01/11/2017	Yes	It focuses on sustainably managing and developing coastal forests for climate change adaptation, emphasising coastal protection forests and central government funding for approved projects (Jhaveri et al., 2018).
Law 16/QH14[47]	15/11/2017	Yes	The Forestry Law covers forest management, protection, development, and utilization, along with the processing and trading of forest products to promote sustainable forestry practices and preserve natural resources in Vietnam.
Law 18/QH14[48]	21/11/2017	Yes	Amends the Fisheries Law of 2003; regulates the exploitation and management of fisheries resources in Vietnam, including those in mangrove ecosystems.
Decision 79/QD-TTg[49]	18/01/2018	Yes	Promulgates the National Action Plan to develop Vietnam's shrimp industry to 2025. Sets a target shrimp export value of 10 billion USD, with 8.4 billion USD coming from giant tiger prawn and white-leg shrimp. However, achieving this target will require significant effort, particularly in addressing the issue of small-scale production.
Decision. 622/QD-TTg[50]	10/05/2018	Yes	National Action Plan for Sustainable Aquaculture. To encourage shrimp farmers to change from conventional aquaculture production practices to improved production practices and to promote the implementation of certification systems for the industry (Ngoc et al., 2021).
Decree 156/ND-CP[51]	16/11/2018	Yes	This Decree details the implementation of some articles of forestry Law.
Law 35/QH14[52]	20/11/2018	No[53]	Amends 55/2014/QH13. Law on amendments to articles and 37 Laws. Amends Law on environmental protection no. 55/2014/QH13, land Law 45/2013/QH13.
Decision 523/QD-TTg[54]	01/04/2021 (till 2030)	Yes	Forestry Development Strategy; aims to develop a sustainable mangrove forest management plan for northern Vietnam. It emphasizes the need for more scientific research on lessons learned to provide input for this plan (Trieu et al., 2020).
Decision 111/QD-UBND	08/02/2022	Yes	In this Decision, farmers in Ca Mau can receive three potential economic benefits, including a higher shrimp price for natural shrimps, a premium by using a certified organic brand, and payment for forest ecosystem services (Nguyen et al., 2022).

[44] Quyết định chi tiết thi hành một số điều của luật bảo vệ môi trường [Decree Detailing a number of articles of the Law on Environmental Protection] No. 19/ND-CP (Feb. 14, 2015)

[45] Quyết định ban hành quy chế quản lý rừng phòng hộ [Decision on Promulgating the Regulation on protection forest management] No. 17/QD-TTg (Jun. 9 2015)

[46] Nghị định của Chính phủ: Quy định về xử phạt vi phạm hành chính trong lĩnh vực tiêu chuẩn, đo lường và chất lượng sản phẩm, hàng hóa [Decree of the Government on penalties for administrative violations against regulations on standards, measurement and quality of goods] No. 119/ND-CP (Nov. 1, 2017)

[47] Luật Lâm nghiệp [Law on Forestry] No. 16/QH14 (Nov. 15, 2017)

[48] Luật thủy sản [Law on Fisheries] No. 18/QH14 (Nov. 21, 2017)

[49] Quyết định số của Thủ tướng Chính phủ: Về việc ban hành Kế hoạch hành động quốc gia phát triển ngành tôm Việt Nam đến năm 2025 [Decision of the Prime Minister on introducing the national action plan on development of Vietnam's shrimp industry by 2025] No. 79/QD-TTg (Jan. 18, 2018)

[50] Quyết định về việc ban hành kế hoạch hành động quốc gia thực hiện chương trình nghị sự 2030 vì sự phát triển bền vững [Decision on National Action Plan for Sustainable Development Agenda], No. 622/QD-TTg (May 10, 2017)

[51] Nghị định quy định chi tiết thi hành một số điều của luật lâm nghiệp [Decree detailing the implementation of a number of articles of the forestry Law] No. 156/ND-CP (Nov. 16, 2018)

[52] Luật sửa đổi, bổ sung một số điều của 37 luật có liên quan đến quy hoạch [The Law of amendments and supplements some articles of 37 Law related to planning] No. 35/QH14 (Nov. 20, 2018)

[53] This Law is repealed according to FAOLEX, but not according to ECOLEX. It is not stated which new Law has come in to place of this Law.

[54] Quyết định phê duyệt chiến lược phát triển lâm nghiệp việt nam giai đoạn 2021 - 2030, tầm nhìn đến năm 2050 [Decision Approving the Viet Nam Forestry Development Strategy in the 2021-2030 period, with a vision to 2050] No. 523/QD-TTg (Apr. 1, 2021)

3. STUDY AREA

Shrimp farming constitutes approximately 25% of Vietnam's total export revenue (de Graaf & Xuan, 1998). According to the General Statistics Office, the Mekong River Delta contributed 83.6% of Vietnam's shrimp farming production in 2020, with Ca Mau Province being the leading contributor at 24.8%. Vietnam's mangrove forests are distributed across four zones, with Ca Mau Province in Zone IV. With a total area of 191,800 hectares, it is the most extensive and nutrient-rich mangrove ecosystem with optimal conditions for mangrove growth, including low-lying topography, abundant alluvial deposits, and favourable water currents (Hong & San, 1993). Ca Mau has the most substantial mangrove area, which aligns with the Province's focus on sustainability by integrating mangroves into shrimp farming practices (Ahmed et al., 2017; Quach, 2018). For this research, Ca Mau is chosen as the study area.

3.1. Geographic location and study area location

Vietnam is a Southeast Asian tropical country (Nguyen, 2015), extending from 8°50'N to 23°20'N along the southeastern margin of the mainland (Luong, 2014). Vietnam's administrative units consist of the provincial, district, and communal levels (consisting of several villages). Vietnam is divided into five municipalities and fifty-eight administrative Provinces, and its total land area is 33.038.000 ha (Nguyen, 2015). In Vietnam, there are two essential river deltas; in the north, the Red river delta, and in the south, the Mekong river delta, integrated with massive mangrove systems, forming most of the world's coastal mangroves (Veettil et al., 2019). Ca Mau has a low and flat terrain (Tinh et al., 2009). In-depth research on district-level mangrove management is done in a sub-study area within Nam Can District; see Figure 3 below. Maps were elaborated using Geographic Information System software QGIS and data from Google Earth Imagery (2022), obtained by installing the XYZ file of the QGIS plugin 'Google Satellite'.

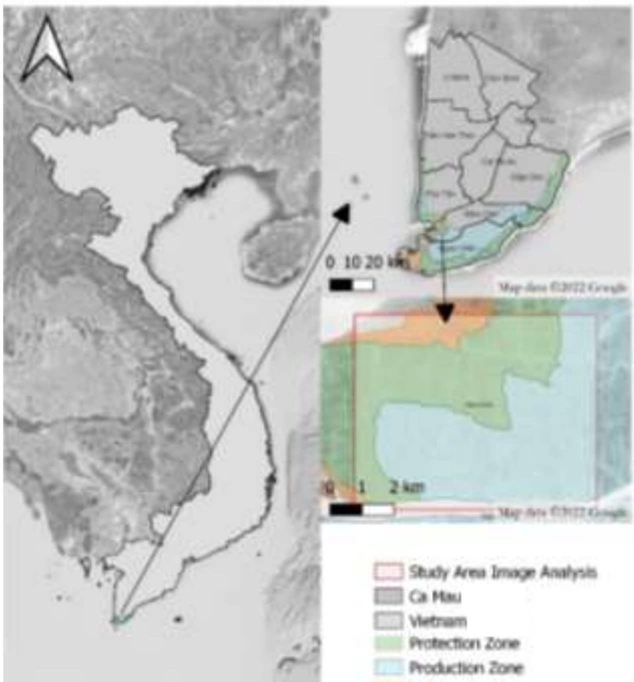


Figure 3 Study area Ca Mau Province - Nam Can District within Vietnam. Including the protection (green overlay), production (blue overlay) and special-use (orange overlay) zone.

3.2. Climate

Vietnam is a tropical country, and the climate of Ca Mau has a tropical monsoon with a dry season from December to April, dominated by an east-northeast wind direction, and a rainy season from May to November, dominated by the west-southwest wind direction (Tinh et al., 2009; Stoop et al., 2015). Ca Mau has high humidity and often is cloudy. The Province is regulated by two conflicting tidal regimes: the East Sea, which is a large amplitude semidiurnal tide, and the West Sea, which is a diurnal tide of smaller amplitude, causing a complex saline-freshwater interaction, according to the Sub-Institute for Water Resources Planning (Vietnam) (SIWRP, 2008). This is suitable for brackish aquaculture (Son et al., 2015).

3.3. Vegetation

The current forest area of Ca Mau Province covers 108,025 hectares, with 11,647 hectares of wasteland designated for reforestation and 96,378 hectares of forested areas. Of this, 66,656 hectares consist of mangroves, accounting for 61% of the total forest area. These mangrove forests are vital for coastline protection, mitigating wave and storm impacts, local climate stabilising and serving as a source of wood, fuel, and feeding and nursing areas for many aquatic species with economic value in Ca Mau (Ha et al., 2012b). Circular 34[55] (2009) categorizes forests, including mangroves, based on use purposes, formation, geographical conditions, tree species, timber reserves, and land without forests planned for forestry. Mangroves are classified as special-use, production, or protection forests based on use purpose and as natural or plantation forests based on formation. Natural forests are further subdivided into primary and secondary forests, with primary forests having their original structures and not influenced by humans. Secondary forests are categorized as either restored or post-exploitation forests. Plantation forests may also be formed on lands without forests or generated naturally after the exploitation of forest plantations.

Ca Mau had more than 1,300 kg of Agents Orange and Agent White (herbicides) dumped between 1966 and 1970, which caused a loss of 52% of its mangrove coverage. According to the Environmental Justice Foundation, a significant proportion was replanted in the later years, but large areas were again converted to aquacultural practices along the coast (EJF, 2003). Table 4 below shows the mangrove use in Vietnam by area in 2020 per forest management zones.

Table 4 Mangrove use in Vietnam by area (ha) in 2020 (adapted from Thuy et al., 2022). Categorized in the production, protection and special use zone.

		Forest management zones		
	Mangrove forest (ha)	**Production forest (ha)**	**Protection forest (ha)**	**Special use forest (ha)**
Total	256.310	71.214	164.656	20.440
Forest covered area	150.107	29.764	107.052	13.291
Natural forest	54.751	4.984	40.151	9.615
Plantation	95.356	24.779	66.901	3.676
Forest land/area	106.203	41.450	57.604	7.149
Afforestation (young forest) area	10.802	3.674	6.862	267
Restoration area	1.170	160	826	185
Others	94.230	37.616	49.916	6.698

[55] Thông tư quy định tiêu chí xác định và phân loại rừng [Circular on criteria for forest identification and classification] No. 34/TT-BNNPTNT (Jun. 10, 2009)

3.3.1. Mangrove species

Mangrove trees are typically found in tropical and subtropical areas along muddy coasts and rivers, with adaptations such as aerial roots to withstand harsh conditions such as elevated temperatures, low oxygen levels (Veettil et al., 2019) and salinity variations (Mark et al., 2021a). Mangroves' morphological, anatomical, and physiological adaptations enable them to survive in such environments (Göltenboth & Schoppe, 1993). Root parts allow for gas exchange with below-ground parts through air holes or lenticels. Below-ground parts comprise the absorbing/anchoring component and cable roots, which unify the former with the aerating parts (Marchand, 2008). The Food and Agriculture Organization (FAO) identifies fifty mangrove species worldwide, with four main genera: *Rhizophora, Bruguiera, Sonneratia*, and *Avicennia* (Veettil et al., 2019). In Ca Mau, *Rhizophora apiculata* (red mangroves) and *Avicennia alba* (black/grey mangroves) are the most prevalent species (McEwin & McNally, 2014; Portengen, 2017). Research has shown that in 1992 the diverse mangrove forests of Ca Mau were replaced by mono-culture forests primarily consisting of planted *Rhizophora apiculata* (Đước), the dominant species in extensive shrimp farms (Ha et al., 2014; Vo et al., 2013). *Rhizophora apiculata* has large dark green and glossy leaves, with a mean growth rate of 0.99 m/y in the first ten years (Portengen, 2017). *Rhizophora apiculata* has prop roots, allowing gas exchange with below-ground parts through air holes or lenticels (Marchand, 2008). The timber of *Rhizophora apiculata* is in high demand for firewood and charcoal (high market value), making it a preferred species for replanting in the area. *Avicennia alba* (Mấm trắng), which has pneumatophores and is crucial for coastal protection, can be found in the Protection Zone, while Nipa is planted in waterways to protect banks from erosion and for roofing or selling purposes (Ha et al., 2014; Marchand, 2008; Portengen, 2017); see Figure 4 below.

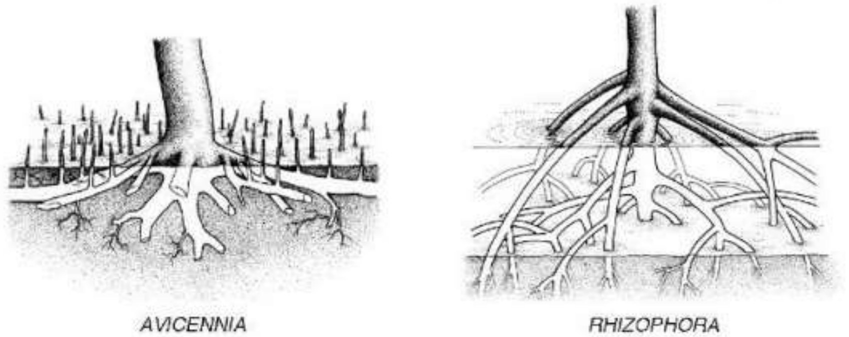


Figure 4 Root system *Avicennia* and *Rhizophora* mangroves (adapted from Ha et al., 2014)

Nipa palm (mangrove palm) is planted in the waterways to protect the banks from erosion and to use the leaves for roofing or selling for cash (Ha et al., 2014). Research has shown that the remaining mangrove vegetation on the Vietnamese coastlines consists mainly of secondary plant communities and that degraded soils limit the regeneration of new vegetation (Veettil et al., 2019; Goldberg et al., 2020). Research by Pham (et al., 2020) showed a primarily natural regeneration of *Avicennia* Forest in the study area within Nam Can District; see Figure 5 below.

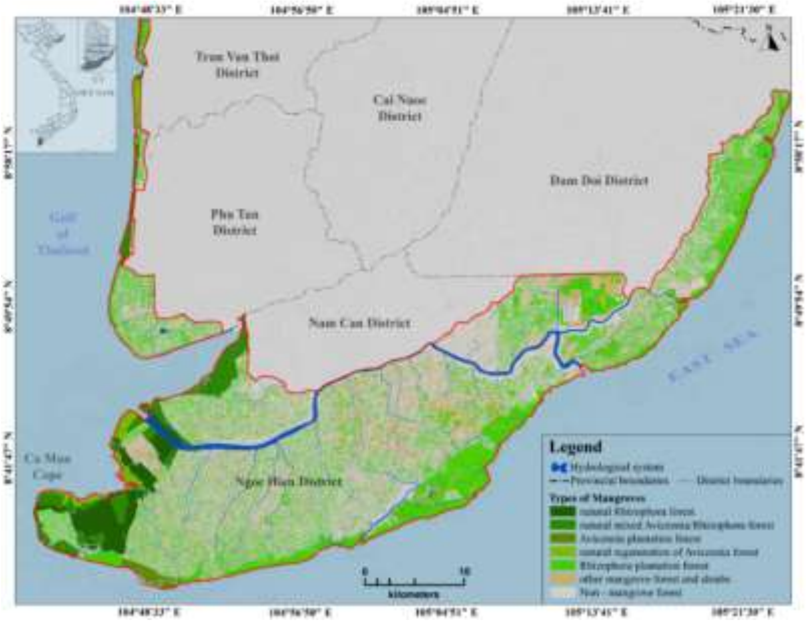


Figure 5 Mangrove forest classification (adapted from Pham et al. 2020)

3.3.2. Field Trip Study Area – Classes on-farm

Ca Mau has predominantly integrated mangrove-shrimp farms (Lai et al., 2022; Tran et al., 2021). In April 2022, a field trip was made to Ca Mau. During this trip, informal interviews with shrimp farmers and forest managers helped frame the research objectives and questions and aid the image classification method. A method was developed for the classification justification (see Methods). The following land cover classes on shrimp farms were found; mud, mud with propagules (mangrove trees of less than a meter high), mixed (light and dark) mangroves (likely young and older mangroves of the same species), dike (with and without grass and or other vegetation), water, and other vegetation in the ponds. Muddy areas often occur when the water level is lowered by opening the sluice gates. See Figures 6 to 12 below for photos of classes present on shrimp farms (photos taken by students of Can Tho University).


Figure 6 Other vegetation


Figure 7 Other trees mixed with other vegetation

Figure 8 Full-grown (*Rhizophora*) mangroves

Figure 9 Dike with grass and other vegetation

Figure 10 Mud

Figure 11 Burnt mangroves for charcoal

Figure 12 Mud with propagules

3.4. Mangrove management in Ca Mau

Integrated mangrove-shrimp farmers in Ca Mau are located within the production and protection zone, both zones that are covered by the buffer and full protection zone (Ha et al., 2012a). After the Land Law of 2013 (45/QHB[56]) was implemented nationally, Ca Mau Province gave red certificates to people with agricultural land without forest. Green certificates were given for shrimp farming and mangrove protection to people owning forestland or who had contracts with state forest enterprises or state-owned companies (Ha, 2012b). In Ca Mau, production forest management is managed mostly by forest management boards, households and forest companies, the latter commercially exploiting the forests. Close to 100% of the protection forest is managed by eight Forest Management Boards funded by the national budget (Ha, 2012). See Table 5 below for an overview of three forest types and their management structures in Ca Mau.

Table 5 Land area (ha) of three forest management zones and their management structures in Ca Mau (adapted from Ha et al., 2014). Categorized in the production, protection and special use zone.

	Forest management zones			**Total (%)**
	Production forest	**Protection forest**	**Special use forest**	
National Parks, island units			17.409	16.0
Forest Management Boards	15095	26.102	123	38.1
Scientific Research Unit			272	0.2
Armed force unit	3239	48		3.0
Forest Companies	38245			35.3
People Committee	17			0
House Holds	7023	747		7.2
Total Area	43.619	26887	17805	

3.5. Additional statistics related to mangrove-shrimp farming in Ca Mau

According to the General Statistics Office (2021), Vietnam's total land use area was 522.1 hectares (ha), of which 143.1 ha was used for agriculture, 95.1 ha for forestry, 23.6 ha for 'specially used land', and 6.6 hectares for homes. The General Statistics Office provided data on the amount of protection and production forest in Vietnam, as well as data on the gross output of wood in Ca Mau and the aquacultural production in Ca Mau from 2005 to 2020 (General Statistics Office, 2023b, 2023c, 2023d, 2023e). These statistics are combined in Figure 13 below[57] by the author of this research. It combines on the left hand the total area in Vietnam of forest management zones; production (blue) and protection (orange) (in 1000 hectares) on the national level, and the aquacultural (red) (1000 tonnes) and the wood production (green) (1000 m^3) of Ca Mau (the dashed lines indicate trend lines). Provincial data on the forest management zones and its areas are not available (or could not be found). However, the mangrove forest management zone polygons used for this research (see Methods) show 91.529 ha of special-use, 576.281 ha of production forest and 440.080 ha of protection forest in Ca Mau. The data is shown for the years 2005-2020. The graph shows that forest production has increased in the given period on the national level whilst the protection forests have decreased. In 2016, Ca Mau decreased in both wood production and aquacultural production. There was also an apparent dip in the amount of production forest in 2016 in Vietnam. Overall, in Ca Mau, aquacultural production and wood production have increased.

[56] Luật đất đai [Land Law] No. 45/QHB, (Dec. 9, 2013)

[57] The data for Figure 13 below was obtained from the General Statistics Office of Vietnam, and was used with permission. The figure was created using these data with Excel.

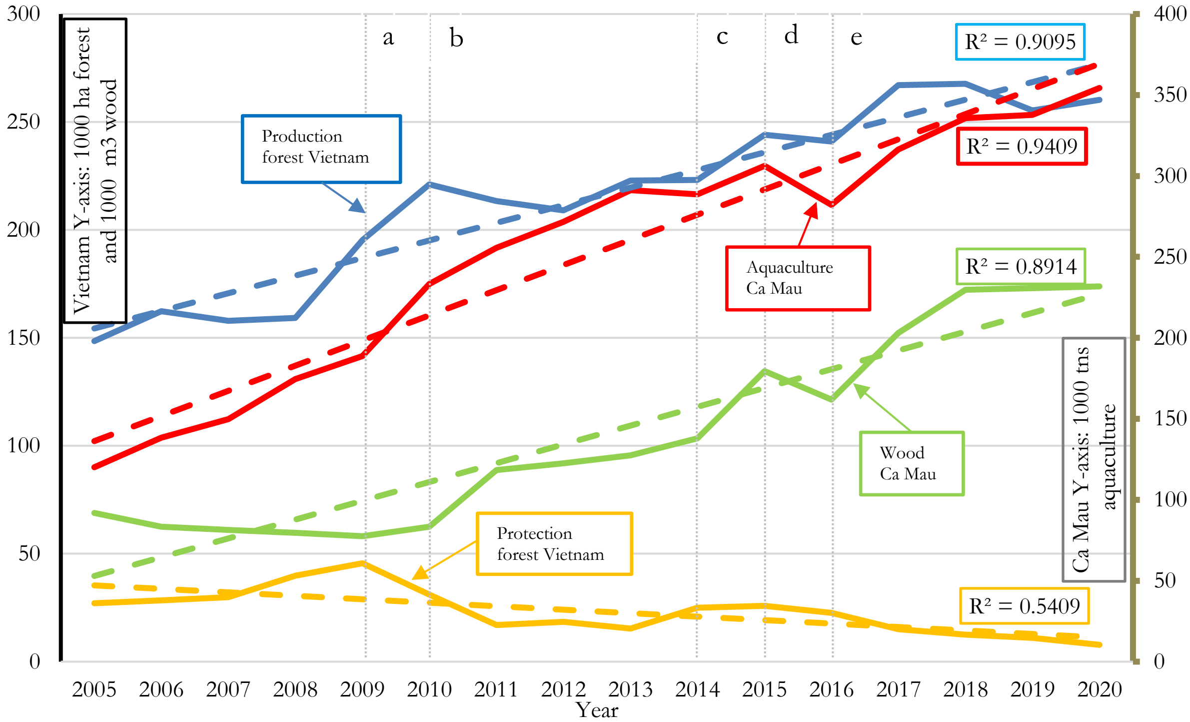


Figure 13 Production and protection forest amounts (in 1000 hectares) on the national level, combined with aquacultural (1000 tonnes) and wood production (1000 m^3) of Ca Mau. Vertical dashed lines indicating trend lines. Figure created with data of General Statistics Office (2023b, 2023c, 2023d, 2023e). R^2 showing the linear regression determintation coefficient (0-1).

The vertical dashed lines a, b, c, d and e indicate a significant shift of the line in the graph. Although legislation takes time before it is implemented by farmers (if at all implemented in practice), the policy framework presented in Chapter 2 could be linked to this Figure[58]. Additional data from the General Statistics Office is shown in Figure 14 below. This data was not put in the same Figure, as part of the data is missing, and these lines would decrease interpretability. The Figure shows that the planted forest was kept steady in Ca Mau between 2008 and 2021. However, almost no newly planted forest has been planted since 2016 (GSO, 2023a).

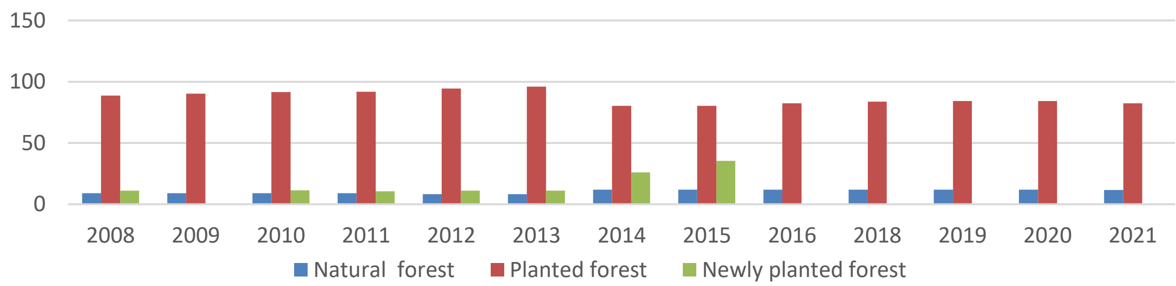


Figure 14 Forest area Ca Mau as of 31 December each year (adapted from GSO, 2023a), 2017 missing

[58] In 2009 (a), the protection forest in Vietnam decreased (steadily) whilst the aquacultural production in Ca Mau increased. Decision 2010 (19/QD-UB) was implemented. In 2010 (b), the production forests in Vietnam decreased while the wood production in Ca Mau increased. The Land Law of 2013 (45/QHB) and the Law on Environmental Protection in 2014 (55/QH13) got implemented. Between 2014 (c) and 2015 (d), aquacultural production increased slightly in Ca Mau. Decision 17/QD-TTg was implemented in 2015, when the aquacultural production suddenly decreased and rose again in 2016, following a similar trend with the wood production in Ca Mau.

4. OVERVIEW OF METHODS AND DATASETS

4.1. Overview of methods

In this section, an overall workflow is provided: the research objectives, (data) inputs, the output of the research objectives, the process, Decisions and data preparations (see Figure 15 below). The corresponding methods and datasets are summarized in Tables 6 and 7 below.

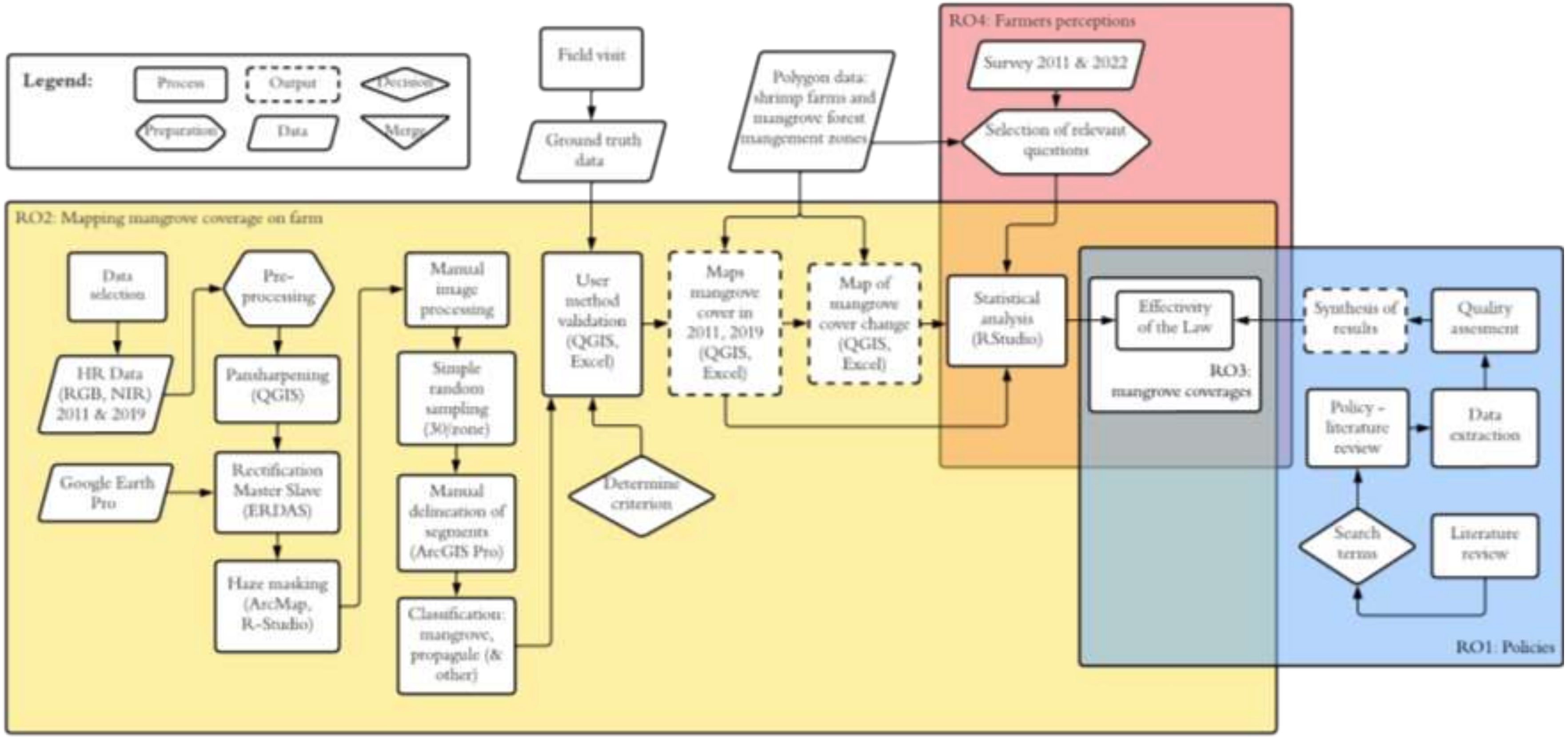


Figure 15 Methods flowchart. Explained per research objective.

Table 6 Overview of research objectives, corresponding methods, software, data sources and results

Research objective	Method applied	Software	Data (source) used	Results
RO1: To determine the differences and similarities between mangrove forest-related legal instruments related to mangrove cover in the different forest management zones in Ca Mau	Policy-literature review	Mendeley	Literature sources, FAOLEX, Luat Vietnam, Công Báo (OFFICIAL GAZETTE), Vietnam Legal Normative Documents and ECOLEX	Table with mangrove forest zones and mangrove cover management requirements
RO2: To analyse the difference between the forest management zones in their mean mangrove cover on-farm in Nam Can District 2011 vs. 2019	Image analysis	QGIS, ArcMap, ArcGIS PRO, Excel, Tableau, RStudio, ERDAS Imagine, eCognition	Quickbird imagery, GeoEye Imagery, Google Earth Pro, administrative boundaries, zoning areas, shrimp farm boundaries, ground truth data	Maps with mangrove cover % on-farms in 2011 and 2019 and a change map. Insight into the changes in land cover.
RO3: To assess whether the remote sensing-based manually delineated mangrove cover on-farm is in line with farmers estimates or other forest policies related to mangrove cover in the different forest management zones	Mangrove coverages analysis	Excel, QGIS, ArcGIS PRO, RStudio	Policy literature-review, image analysis data and survey data, administrative boundaries, zoning areas, shrimp farm boundaries	Statistical output of the comparison of estimates of farmers and remote sensing-based estimates. Insight into the effects of shrimp farm area and distance to open water on mangrove cover on-farm.
RO4: To analyse the motives of shrimp farmers in different forest management zones to maintain or change their mangrove cover on-farm in Nam Can District and Ca Mau Province	Survey (statistics) analysis	Excel, QGIS, ArcGIS PRO, RStudio	Survey data, administrative boundaries, zoning areas, shrimp farm boundaries	Statistical output of the answers given to the chosen survey questions, which help in understanding the reasons for mangrove cover change on-farm

4.2. Overview of datasets

The datasets used in this research are listed below; see Table 7 below.

Table 7 Overview of datasets used in this research. The table shows research objectives, data owners, type and resolution of the data, date of publishing and URL

Research objectives	Name	Variables used	Data owner	Type and resolution	Date	URL
2,3,4	Administrative boundaries	Country, Province, districts level boundaries	OCHA	Vector (polygon) (.shp)	2020	https://data.humdata.org/dataset/cod-ab-vnm
2,3,4	Shrimp farm boundaries	X	Q. T. Vo	Vector (polygon) (.shp)	X	X
2,3	Quickbird satellite imagery	Band 1-4	European Space Agency (ESA)	Raster (pan 0.5m, multispectral 2m) (.tif)	2011	https://discover.maxar.com/
2,3	GeoEye satellite imagery	Band 1-4	European Space Agency (ESA)	Raster (pan 0.4m, multispectral 1.6m) (.tif)	2019	https://discover.maxar.com/
3, 4	Survey 2011	Location respondent, questions: 5.17, 52.27, 52.37	Q. T. Vo	Point data (.shp)	2011	X
3, 4	Survey 2022			Point data (.shp)	2022	X

4.3. Policy –literature review

To analyse the jurisdictional system regarding mangrove management in mangrove-shrimp farms, a review is performed on policies and a policy literature review, hereafter referred to as 'policy – literature review'. This approach was preferred to mitigate the fact that many legal instruments are published solely in Vietnamese and are therefore hard to interpret through translational systems. Moreover, relevant legal documents were not obtainable for free. The policy-literature review involved searching for, collecting, and analyzing relevant literature on a specific policy issue or topic to inform policy analysis. The policy-literature review aimed to provide a comprehensive and evidence-based understanding of the issue or topic under consideration and identify gaps or areas where further research is needed. First, a literature review was performed to identify relevant search terms, after which the policy–literature review was performed. Data extraction, quality assessment and the synthesis of results are explained in the sections below. The policy-literature review results aimed to inform policy development on the current effectiveness of the current mangrove forests management zones; see Figure 16 below.

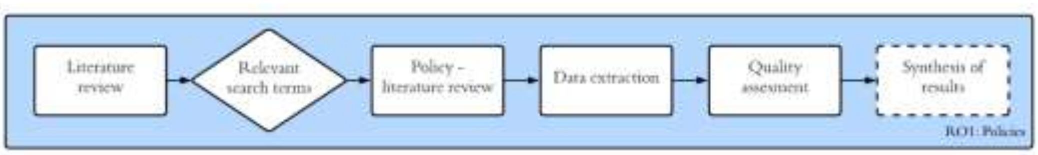


Figure 16 Flowchart method policy - literature review

4.3.1. Literature review and relevant search terms

To find legal instruments, existing literature and documents that fitted the scope of this research, the search terms were extracted from literature research. This determined that the types of documents (Decrees, Decisions, strategies, plans, Laws etc.) were published by different stakeholders. Existing literature was found using search strings 'mangrove management jurisdiction Ca Mau' combined with Boolean search terms, including Decrees, Decisions, strategies, plans and Laws. As mangroves are managed within shrimp farms in Ca Mau, it can be assumed that almost all documentation found would encompass its management within shrimp farms. When finding literature that fitted the research scope, connectedpapers.com was used to find derivative or prior works. Additional online translation plugins were used to translate Vietnamese legal instruments and English search queries to Vietnamese search queries. These online translation plugins were Google Translate and Quick Translation Plugin. Additional help was obtained from students from Can Tho University to understand the legal instruments (as translation occasionally caused misunderstandings). The following websites were searched to obtain policies directly: FAOLEX, Luat Vietnam[59], Công Báo (OFFICIAL GAZETTE), Vietnam Legal Normative Documents and ECOLEX. Legislation exists on national, regional and district levels. The policy analysis aimed to focus on both national and provincial-scale legislation. However, provincial implementation of legislation was found to be more challenging to access and interpret, likely due to translation issues.

4.3.2. Data extraction, quality assessment and synthesis of results

Understanding the development of the legal instruments and the parties involved was essential to identifying and extracting useful information from the selected literature and reviewed policy documents (shown in Chapter 2). Usage of the website of ECOLEX showed whether other documents supported the legal instruments found (Decrees/Decisions/strategies) and whether they were currently repealed or still enacted. Relevance, reliability, and validity were achieved using a systematic policy-literature review. The systematic review of the literature was a rigorous and comprehensive approach that involved identifying, selecting, and critically appraising relevant studies to answer Research Objective 1. The systematic review aimed to provide a thorough and objective analysis of the available evidence on a particular topic and identify any gaps, inconsistencies, limitations, or areas for future research. These are elaborated on in the Discussion. Key findings are summarized in a table, which focuses on obligations regarding mangrove management on shrimp farms.

4.4. Image analysis

The following sections provide a detailed discussion of the approach employed to analyze two satellite images, as depicted in Figure 17 below. These sections delve into various aspects of the analysis, including data selection, data pre-processing, manual image processing, validation of the user method, and the subsequent statistical analysis.

[59] 'Luật việt nam' in Vietnamese, translates to 'Vietnamese Law' in English

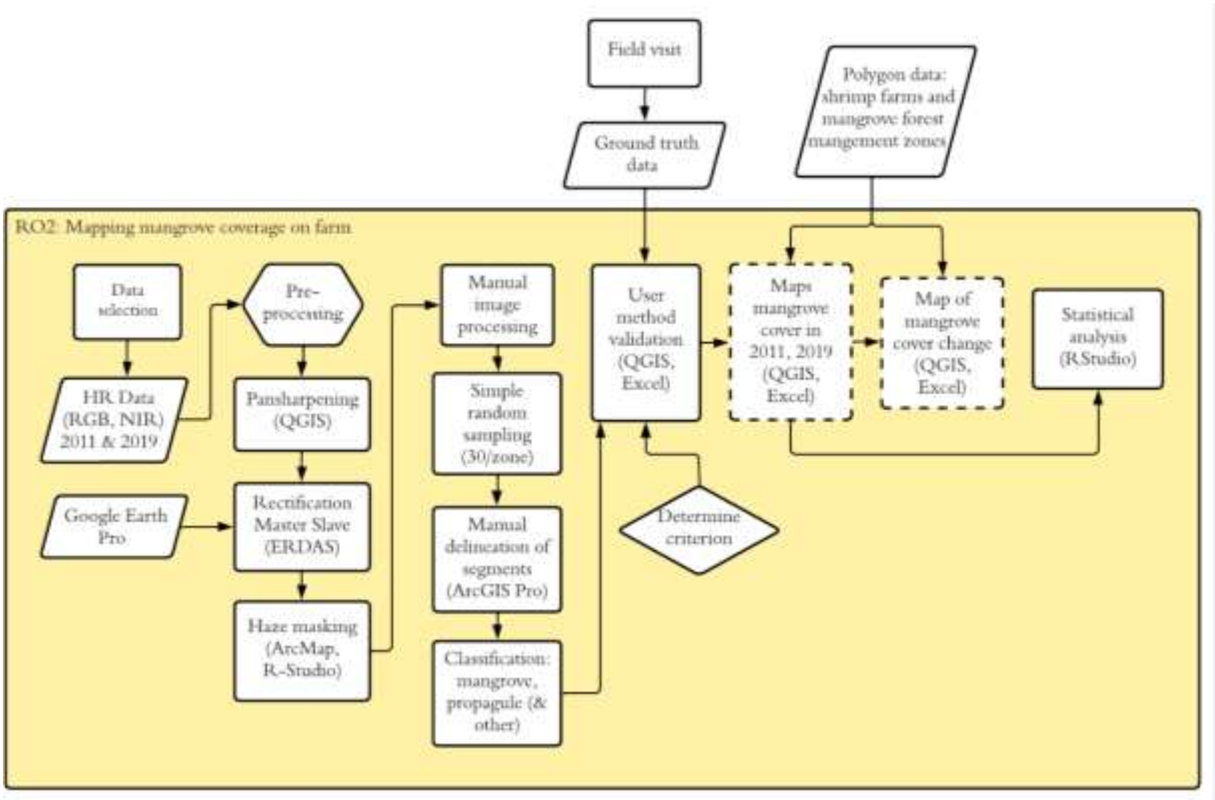


Figure 17 Flowchart method image analysis

4.4.1. Data selection

The satellite data selected for the change detection had to fulfil search requirements discussed with an expert in remote sensing and object-based image analysis: consisting of a cloud cover of less than 20% and an image off-nadir angle of 30 (thresholds confirmed by Tiede et al., 2021). Detecting clouds in optical remote sensing imagery is of utmost importance, as the failure to detect them can lead to inaccurate and misleading results in various analyses (Al Zayed & Elagib, 2017). When the satellite elevation angle is lower, the off-nadir acquisition angle becomes more significant, resulting in a longer optical path. The atmosphere scatters the radiance to the sensor, thereby bypassing the objects on the ground, which will negatively affect classification accuracy (Matasci et al., 2015). Additionally, the satellite imagery had to contain production and protection zone area, which should overlap for change detection. Part of this research aimed to compare the estimates of mangrove cover on-farm to the remote sensing-based manually delineated mangrove cover on-farm to see whether there are significant differences (Research objective 3), therefore the images should preferably have been captured in 2011 and 2022. Due to the limited availability of cloud-free data in the selected study area, combined with the other data requirements as described above, only two images remained suitable for this research: one Quickbird image of 2011 and one GeoEye image of 2019 as available from the European Space Agency (ESA, n.d.-a, n.d.-b); see Table 8 below.

Table 8 Data specifications Quickbird (2011) and GeoEye (2019), as provided by ESA

	2011	**2019**
Map type	Quickbird 2	GeoEye 1
Image ID	101001000CF80C00	105001001A62E800
Date	09/02/2011	22/12/2019
Time	3:14	3:36
Band combination and resolution	Panchromatic : 0.5 m Multispectral Bundle 4-Bands (BLUE, GREEN, RED, NIR1): 2m	Panchromatic : 0.4 m Multispectral Bundle 4-Bands (BLUE, GREEN, RED, NIR1): 1.6m
Spectral range	Panchromatic: 450 - 900 nm Blue: 450 - 520 nm Green: 520 - 600 nm Red: 630 - 690 nm NIR: 760 - 900 nm	Panchromatic: 450 - 800 nm Blue: 450 - 510 nm Green: 510 - 580 nm Red: 655 - 690 nm NIR: 780 - 920 nm
Data type	Map scale orthorectified (OR2A) 1: 50.000	Map scale orthorectified (OR2A) 1:12.000
Cloud cover	0.0%	0.0%
Image off nadir	19.4°	25.8°
Spatial resolution at nadir	Spatial Resolution, IFOV[60]: Panchromatic: 0.61-0.72 m (GSD) Multispectral: 2.4-2.6 m (GSD)	Spatial Resolution at Nadir: Panchromatic: 0.41m Multispectral 1.64 m
Sun elevation	52.1°	51.7°
Max target azimuth	152.6°	153.5°
Kernel	4x4 Cubic Convolution	4x4 Cubic Convolution
Projection	UTM-WGS 84	UTM-WGS 84
Bit depth	16-Bit	16-Bit

4.4.2. Image pre-processing

Using the pan sharpening fusion technique, the high-resolution panchromatic image was fused with the low-resolution multispectral. This produced a higher spatial resolution panchromatic raster of both imageries (0.5m and 0.4m, respectively). The cubic convolution interpolation resampling method was used (Lyons et al., 2018). This is a successful method for resampling high-resolution images for land cover change analysis in the Mekong Delta (Liu et al., 2020). Due to the resampling, spatial shifting required both images to be clipped again to match their extents. Even though the satellite images are orthorectified (Map-Ready 1:50.000 and 1:12.000), pixel alignment was further obtained by Rectification Master-Slave (using ERDAS Imagine) (see Appendix B Figure 46 for supplementary screenshots). GeoEye was chosen as the reference image due to its higher resolution (.4m) than the Quickbird imagery (.5m), as well as visually better matching with Google Earth (GE) imagery. The ortho-correct function *Control Point* was used with a Polynomial Geometric Model consisting of eight ground control points. These eight ground control points had root mean square errors of less than 0.5, which showed sufficient threshold value for accurate resampling (Mas, 1999; personal communication, April, 2022). The Ground Control Points were placed on corners of buildings, as these are assumed static. The Quickbird image was resampled to a pixel size of 0.5m using the bilinear interpolation and the GeoEye reference layer. Smoke was detected on the GeoEye image (due to a

[60] Instantaneous field of view

fire), which could potentially decrease the segmentation and classification accuracy; therefore, this had to be removed. Thin patches were included in the analysis[61], while dense smoke patches were removed from both the Quickbird and GeoEye imagery. Additional polygons were created, covering the unusable and dense hazy areas. When overlap occurred, haze polygons in each band of both images were multiplied by zero. After compositing the individual bands, the final image showed no data in haze areas.

4.4.3. Class selection and digital multi-resolution segmentation

Using the information retrieved on field classes during the fieldtrip (see Chapter 3), the classes on the shrimp farms were determined. Asides from mangroves, propagules (or mangrove propagules/mangrove replanting) can indicate the intent of a farmer to reforest or afforest mangroves on-farm or indicate that logging just took place. Therefore, these two classes were chosen for segmentation and classification (further explained in the sections below). The remaining area on-farm is classified as other.

The study area consists of 832 shrimp farms (which are not covered by smoke), with many fine patches of mangroves and propagules. Several methods for segmentation and classification were applied, and the best-fitting method for image segmentation and classification was chosen (as further described hereafter and in Sections 4.4.5 and 6.2.2). Object-based image analysis and classification are effective and more accurate than a pixel-based method for image analysis of high-resolution imagery (Whiteside et al., 2011), especially for the segmentation of mangroves (Salehi et al., 2012). Due to the increasing availability of very high-resolution imagery, object-based image analysis has been used more frequently (Kavzoglu & Tonbul, 2017). Several studies have successfully performed object-based image analysis to analyse mangrove forests (Son et al., 2015; Suyadi et al., 2018; Tong et al., 2004; Virdis, 2014; Vo et al., 2013). Object-based image analysis combined with multiresolution segmentation is one of the most commonly used segmentation algorithms in eCognition software (Xue & Lin, 2020). Accuracy assessment of image segmentation is crucial to successful image classification using object-based image analysis (Costa et al., 2018).

Multiresolution segmentation was performed in eCognition on both the 2011 and 2019 imagery. However segmentation results did not provide sufficient segmentation accuracy (<80%) after polygon matching. For 100% accuracy, there should be a one-to-one overlap/correspondence between human-identified objects (training objects) and digitally acquired segments (Clinton et al., 2008). Better segmentation accuracy leads to better classification accuracy, and the higher the resolution of the imagery, the higher the accuracy can and should be (Hossain & Chen, 2017). Simple random points were assigned to the exported segments created by multiresolution segmentation (50). These segments were manually delineated to determine segmentation accuracy. Multiresolution segmentation did not provide sufficient segmentation accuracy (<80%); dark pixels occasionally cut up mangrove patches that were not delineated as separated or the other way around. Additionally, mangroves in the ponds or connected to the dikes count as mangrove coverage (personal communication, forest manager, April, 2022). The separation of mangroves from other trees on dikes could not be achieved; see Figure 18 below. Consequently, manual segmentation and classification were chosen, as described further in the sections below.

[61] However, the thin patches were removed for digital segmentation using the ATCOR haze reduction function in ERDAS Imagine. For this, the solar and sensor zenith and azimuth were calculated.

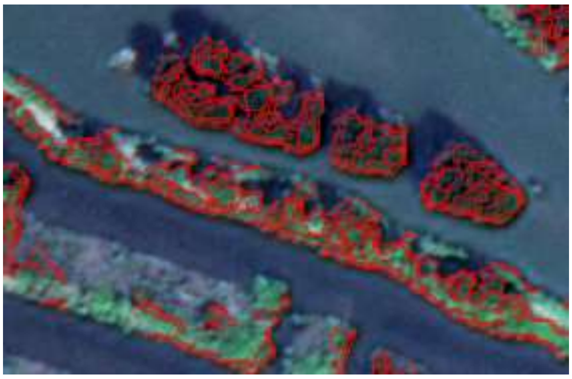


Figure 18 Digital multi-resolution segmentation result example. Red lines indicate segmentation lines as a result of multi-resolution segmentation and object-based image classification of GeoEye Image 2019

4.4.4. Mangrove requirement

Manual delineation allows for highly accurate segmentation and classification based on the specific mangrove cover requirements, such as a height of at least 1m. According to Decree 156 of 2018[62], a mangrove tree must be at least one metre in height, scattered or connected (minimum area not required) to be measured for official 'coverage' on-farm. Mangroves in the shrimp farm pond or connected to dikes (or anywhere on the farm) count as coverage on-farm. No circumference requirements are mentioned in this Decree. The height of the mangrove tree can be estimated using the shadow; see Table 9 below for the values. If the height of the mangrove tree must be larger than 1 metre, using the solar and sensor azimuth and zenith can help calculate the minimum length of the shadow of a mangrove tree of one metre high would be (see Appendix C Figures 47 and 48).

With a mean sun elevation of 52.1 ('e') in both cases, the minimum shadow length can be determined as 1.2845 meters using the formula 1/tan (52.1). Considering the pixel sizes of the satellite images, it is necessary to detect at least three pixels of shadow for 0.5 resolution (equivalent to 1.5 meters of shadow), and at least four pixels for 0.4 resolution (equivalent to 1.6 meters of shadow). This analysis allows us to classify mangrove trees of at least 1.9 meters tall in the 2011 image and 2.1 meters tall in the 2022 image, almost double the required height. However, using fewer shadow pixels could lead to the incorrect classification of mangroves that have not yet reached the required height, leading to an overestimation.

Table 9 Sensor and solar angles. Mangrove tree height of one meter is indicated by a *

	2011 Quickbird Imagery	2019 GeoEye Imagery
Sensor azimuth	240	325.7
Solar azimuth	148.4	128.1
Sensor zenith	3	19.7
Solar zenith	37.9	37.9
Mean satellite elevation	87	70.3
Mean sun elevation (e)	52.1	52.1
Min shadow length (L)*	1.2845	1.2845
Pixel size	0.5m	0.4m

[62] Nghị định quy định chi tiết thi hành một số điều của luật lâm nghiệp [Decree detailing the implementation of a number of articles of the forestry Law] No. 156/ND-CP (Nov. 16, 2018)

4.4.5. Manual image processing

In total, 120 farms (the same 60 shrimp farms in 2011 and 2019) were manually sampled for mangroves and propagules using a Wacom Intuos CTH490. It was chosen to do simple random sampling and assign thirty shrimp farms in the production and protection zones in the 2011 Quickbird and the 2019 GeoEye satellite imagery (repeated measures). This was done without bias and therefore is regarded as a representative sample. 7807 segments were manually delineated and immediately classified (mangrove/propagule) for 2011 Quickbird imagery and 5975 segments for 2019 GeoEye imagery.

A student of Can Tho University manually delineated the shrimp farm boundaries used; see Figure 19 below. The shrimp farm boundaries were converted into shrimp farm polygons. The shrimp farm boundaries were overlayed with the segmented mangrove and propagule polygons using the Overlap Analysis tool (QGIS). This tool computes the overlap between features in an input layer (shrimp farm boundaries) and selected overlay layers (mangrove and propagule polygons). It then adds new attributes to the output layer that show the total overlap area and percentage for each input feature and overlay layer. The resulting output layer contained 60 rows with shrimp farms and columns with information on the area and percentage of mangroves and propagule in each farm. This was done four times, using the same shrimp farm boundaries but different overlay layers (mangroves and propagules of 2011 and of 2019). This data was exported to Excel as a .csv file, and the residual class 'other' was computed by subtracting the mangrove and propagule class areas of the shrimp farm area (area and percentage).

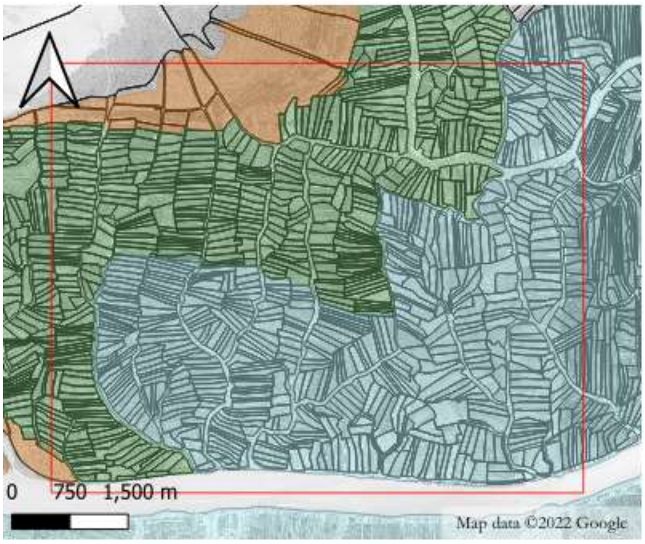


Figure 19 Shrimp farm boundaries and study area.

The mean area of mangroves, propagules, and the other class in each mangrove forest management zone was calculated by adding the cover percentages of each zone and dividing the sum by 30 (n), see Formula (1) below:

Mean class cover (mangrove/propagule/other) within a zone (%) = $\sum$ (class cover %) / n (1)

To calculate the mangrove change per shrimp farm, the percentage of mangroves on a farm in 2011 was subtracted from the percentage of mangroves and propagules on the same farm in 2019 (Excel), see Formula (2) below:

Mangrove change per shrimp farm (%) = Mangrove Cover 2019 (%) - Mangrove Cover 2011 (%) (2)

Land cover changes were calculated using the Overlap Analysis tool (QGIS), similarly as described above. Three separate calculations were performed on the mangrove, propagule and other class polygons of 2011. These separate layers with classes were overlayed with all the class coverages in 2019, which resulted in specific land cover change statistics; see Figure 20 below. E.g. if the 2011 image consisted solely of propagule, 25% remained propagule in 2019, 50 was converted to mangroves and 25% to other. This method shows how the land cover types detected in 2011 were classified in 2019.

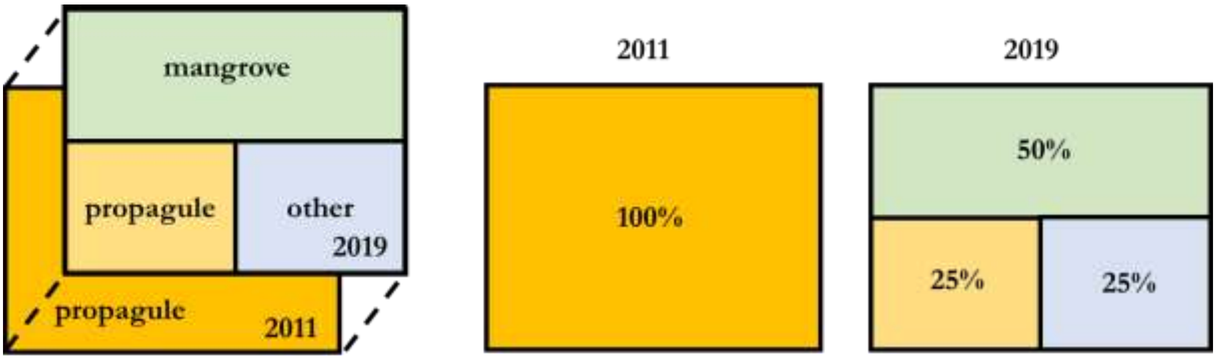


Figure 20 Simplified example of method on specific land cover changes

4.4.6. User method validation - field trip

As farms are private property, and the visitation of foreigners needs to be validated by the government, the final data was collected by students of Can Tho University. Limited accessibility of shrimp farms due to private properties, canal infrastructure, and time constraints resulted in eight randomly selected farms in the production zone and twelve in the protection zone being used for the classification method validation (see Appendix D for the instruction sheet and extra information on the method applied). Students used a GPS device to determine the coordinates of their position (waypoints). From a distance, eight different classes of patches were determined and segments on randomly selected farms were classified accordingly into; mixed mangrove, dark mangrove, mud, mud combined with mangrove propagules, water, dike with trees and grass, dike with trees, and dike with grass. An extrapolation of the classification method is used to determine the classification accuracy of the manually segmented propagules and mangroves (see Appendix E Tables 20 and 21 for the method classification validation sheet).

A photo was taken because it was impossible to go onto the farm and measure the specific waypoints of a segment/class. The waypoints, photos and corresponding assigned classes were imported in ArcMap on a base map of Google Earth (GE) imagery of 2022. This combination allowed for a more precise location of the patches of classes. The waypoint positions were manually edited in the GIS programme to the segment location of the photo using the GE imagery. The location of the segments selected for classification in the field in 2022 was exported to the 2011 and 2019 images. Overlap between 2022 selected segments and segments in 2011 and 2019 was visually classified. These classes were exported to Excel, resulting in a classified segment for 2011, 2019 and 2022 at the same locations. To validate the method used, sixty-four combinations of all classes (8*8) were determined and were assigned values according to the quantity of mangroves: decrease, increase, neutral, or not possible. These values differ between scenarios A (2011 vs 2019) and B (2019 vs 2022). Various factors influence mangroves' height and crown, including the species and environmental conditions. The maturation cycle of mangrove forests lasts for a period ranging from 10 to 20 years, while their lifespan is usually around 100 years (Stringer, 2023). Patches with propagules of 2019 will in 2022 definitively not have grown into patches with a mature mangrove forest due to their growth rate of 1 meter per year (Portengen, 2017), which in three years would approximately correspond to a crown diameter of 2 to 2.5 meters (Galvincio & Popescu, 2016). Within its lifespan, a mature mangrove cover would reach a crown diameter of 10 to 12 meters (Stringer, 2023). Therefore, propagule polygons in 2019, classified as mature mangroves in 2022, were assigned the value *not possible*. Between 2011 and 2019, a mud (or mud combined with mangrove propagule) patch can grow into a mangrove patch. The classes determined visually in 2011 were combined with the visually determined classes in 2019, and the latter was combined with the fieldwork classes of 2022. Using the assigned values, the method was valid in more than 80% of the cases.

4.4.7. Statistical analysis

After conducting exploratory data analysis on the segmentation results, a statistical analysis was performed to determine the significance of the difference in mangrove area between two mangrove forest management zones - the production and protection zones. This analysis was performed in a similar manner to determine the significance of the difference in propagule area between two mangrove forest management zones.

Outliers were determined using the interquartile range. This rule determines that a measurement is an outlier if the value exceeds 1.5 * the interquartile range (IQR) above the third quartile or below the first quartile. Measurement is an extreme outlier if it exceeds 3 * this IQR. After assessing normality using quantile-quantile plots and Shapiro-Wilks assessment, confirming variance and covariance, and including any outliers as defined by the IQR rule, a two-way mixed analysis of variance (ANOVA) was conducted. This was executed to assess the effects of time (within-subjects) and zoning area (between-subjects) on the mangrove cover (dependent variable). All statistical analysis was conducted using RStudio[63]. A two-way mixed ANOVA's assumptions include normality, homogeneity of variance, independence, sphericity and random sampling. In this type of ANOVA, one independent variable (time) is a within-subjects factor, meaning that each shrimp farm is measured on both levels (in 2011 and 2019) of this variable. The other independent variable (zoning area) is a between-subjects factor, meaning that different groups of shrimp farms are assigned to each level (production and protection) of this variable. This resulted in a 2x60x2 design. The effect of time in a two-way mixed ANOVA refers to the main effect of the within-subjects factor (i.e., the effect of the two different time points -2011 and 2019- on the outcome measure -mangrove cover on-farm). The main effect of time shows whether there is a significant difference in the outcome measure between the two time points, regardless of the zoning areas. This could indicate if policies are applied and enforced so that there is mangrove restoration. The effect size was determined using Phi (φ), and categorized into: no, negligible, weak, moderate, strong and very strong relationships (Glenn, 2023). Simple main effects were tested using the Mann-Whitney U and Kruskal-Wallis tests. These tests were preferred because they enable the comparison of two or more independent groups with different sample sizes and are appropriate for ordinal, non-normally distributed data, and are not sensitive to outliers (Kimdung et al., 2013). The Kruskal-Wallis test assumes at least five observations in each group. The following three sets of null and alternative hypotheses of the statistical analysis were set up to analyze the mangrove cover on-farm:

The main effect of zoning area:

> H_0(1): the mean mangrove cover percentage on-farm is equal for production and protection zone; there is no main effect of zoning area on mean propagule cover percentage.
>
> H_1(1): the mean mangrove cover percentage on-farm is not equal for production and protection zone; there is a main effect of zoning area on mean propagule cover percentage.

[63]R is a free, open-source statistical programming language

The main effect of time:

H_0 (2): the mean mangrove cover percentage on-farm is equal for 2011 and 2019; there is no main effect of time on mean propagule cover percentage.

H_1 (2): the mean mangrove cover percentage on-farm is not equal for 2011 and 2019; there is a main effect of time on mean propagule cover percentage.

Interaction effect of zoning area x time:

H_0 (3): there is no interaction effect of zoning area and time on the mean mangrove cover percentage on-farm.

H_1 (3): there is an interaction effect of zoning area and time on the mean mangrove cover percentage on-farm.

4.5. Mangrove coverages analysis

A mangrove coverages analysis is performed to answer research objective 3. This analysis is aimed at linking the remote sensing-based manually delineated mangrove cover results to farmers' estimates and policies in force. This can show insight into farmers' awareness of their current mangrove cover. This can help to determine whether the current forest policies related to mangrove cover are in line with the actual mangrove cover on-farm in the different forest management zones; see Figure 21 below.

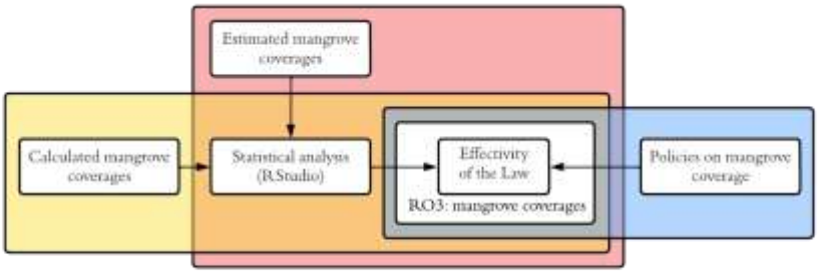


Figure 21 Flowchart method of mangrove coverages analysis

4.5.1. Mean estimated mangrove cover

The estimated mangrove cover on-farm (a question in the Survey of 2011 and 2022) was analysed in both years between both mangrove forest zones in Ca Mau and within Nam Can. These were non-repeated measures. This was performed as an intermediate step in the analysis of the differences between the estimated and manually delineated mangrove cover on-farm. This step allows for interpreting a general change in estimation and whether Nam Can District has a different means of estimation than Ca Mau.

The farms chosen for manual delineation differ from those chosen for the survey, which omits the possibility of direct linkage between the related research objectives on their estimates of mangrove cover in 2011 and their measures of mangrove cover in 2011 by using satellite data. This was because the satellite data only covered a small portion of Nam Can, and only a limited number of respondents were within the area covered by the satellite. Therefore, a simple random sampling method was used for the satellite data.

This data is used to compare the means of the estimated mangrove cover on-farm to the manually delineated mangrove cover on-farm in 2011 in Nam Can. In the manual segmentation, the mean mangrove cover percentage was calculated. The minimum, mean, maximum and standard dev min, and standard deviation max have been calculated for the estimated mangrove cover on-farm by the farmers (survey data) and the manually delineated mangrove cover on-farm, using Excel and RStudio, respectively. The standard deviation has been calculated where x = each value in the set of samples, $\bar{x}$ = the mean (statistical mean) of the set of values. One no-data row in the percentage of mangroves estimated by the farmer was deleted in 2011. The sampling locations of the respondents in 2011 are not the same as those of the manually delineated farms in 2011. However, a general interpretation can be made of the results. Statistical tests were performed using the Wilcoxon test and calculating the effect size[64].

4.5.2. Correlation of shrimp farm size and mangrove cover

The implementation of mangrove cover on a shrimp farm can be influenced by the size of the farm and its management practices. Larger shrimp farms may have more resources and capacity to implement more mangrove cover, but they may also face challenges due to the scale of their operations, including higher production volumes, complex logistics, and greater regulatory requirements. Additionally, Decision 24/QD-UB of 2002 requires a specific correlation between shrimp farm area and the amount of mangrove cover implemented, with recommended percentages for different farm size groups. A mangrove cover of 50%, 60%, or 70% of the total area of farms having less than 3 ha, 3-5 ha, or more than 5 ha should be obtained. This means a mangrove cover of 1.5 ha for the first group, 1.8 ha to 3 ha for the second group, and a minimum of 3.5 hectares for the last group. This Decision was repealed in 2010, but as the implementation of legal instruments has been slow (Ha et al., 2012b) and mangrove coverages on-farm are not changed overnight, the spatial effects of this Decision may still be visible in the satellite imagery of 2011 and 2019. This analysis is performed on the mangrove percentage coverage on shrimp farms and the area of mangroves on-farm. Pearson's Correlation test was used to test the relation between the shrimp farm size and the mangrove coverage on-farm. This test is chosen does not make any normality assumptions and is very sensitive to outliers. The Decision was made to focus solely on analysing the correlation of the remote sensing-based manually delineated mangrove cover on-farm in Nam Can, rather than also including the estimated mangrove cover data points of the survey. This is because the exact shrimp farm areas are only known of the aforementioned.

4.5.3. Distance to open water

The Ca Mau forest area comprises distinct forest management zones, namely special-use, production, and protection, which are situated within other zones, as outlined in Decision 116/1999/QD-TTg[65]. These zones are classified as the full protection zone (FPZ), buffer zone (BZ), and economic zone (EZ) based on their distance from open water. Specifically, the full protection zone pertains to areas within less than 500m from the open water, the buffer zone spans from 500-4000m, and the economic zone encompasses locations situated more than 4000m away from the open water, as noted by Tran et al. (2015). A mangrove coverage of 60% should be followed in the buffer zone. According to Christensen et al. (2008) this is a ratio for mangrove-to-pond of 60:40. Integrated mangrove-shrimp farms are located in the buffer zone, and extensive shrimp farms are in the economic zone. For the economic zone, no specific ratio is evident. No farms should be present in the full protection zone(Vo et al., 2015). To determine whether these three zones significantly influenced the mangrove management on-farm in Ca Mau, the distance of survey points to open water was calculated and consequently categorized as full protection zone, buffer zone or economic zone. This analysis is performed on both the 2011 and 2022 data of the surveys. The study area chosen in Nam Can is located in the buffer zone. Therefore the analysis is performed on the estimated mangrove cover (2011, 2022) and not the remote sensing-based mangrove cover (2011, 2019).

[64] Hypothesis are not ellaborated upon, as many statistical tests were executed.

[65] Quyết định của thủ tướng chính phủ về việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoratoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

The distance to open water was added as a variable by using the survey data points as input features and the outline of Ca Mau as near features, calculating the shortest distance to the coast in the Planar method (near analysis tool - ArcGIS Pro). This was added as a column to the dataset. This dataset was exported as a .csv file to Excel and imported into RStudio. Kruskal-Wallis's chi-squared test with Bonferroni adjusted p-value, and the consequent post hoc Wilcoxon test using Bonferroni's adjusted p-value were used to examine the differences in mangrove cover between the full protection zone, buffer zone or economic zone based on their distance to open water as identified above.

4.6. Survey analysis

The sections below explain the research design and methods of the survey analysis. They show how the study was designed and carried out. The sections describe the research approach, research design, study population and sample, sampling technique, data collection instruments and procedures, and mostly the secondary data analysis techniques, as the survey data was obtained via the external supervisor (Q. T. Vo); see Figure 22 below for the general workflow.

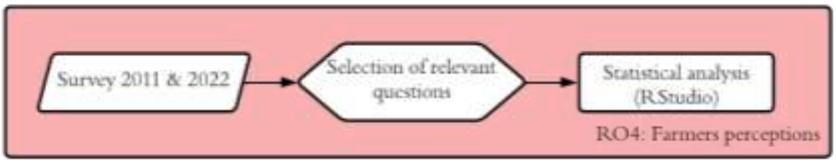


Figure 22 Flowchart method survey analysis

4.6.1. Research approach, design and study population sampling

Face-to-face, non-repeated surveys amongst shrimp farmers in Ca Mau Province were performed in 2011 (n=221) and 2022 (n=152). These surveys included qualitative en quantitative questions regarding their mangrove forest management on-farm (see Appendix F for the survey questions). To analyse the survey data, the data was first filtered on location; the survey data points were imported in ArcGIS Pro, overlayed with polygons of the mangrove forest management zonation areas, and assigned accordingly to a zoning area: production and protection. All points outside of these zonation areas are removed; this resulted in 148 respondents in 2011, of which 105 were in the production zone, and 43 were in the protection zone. In 2022 there were finally 138 respondents, 92 were in the production zone, and 46 were in the protection zone. By overlaying the district polygons on the survey points, a column was added to the datasets that classified the respondents into the following districts: Nam Can, Ngoc Hien, Tan An, Phu Tan and Dam Doi. As mangrove forest management is different depending on the district, an in-depth analysis is done on farmers' responses in Nam Can District; see Figures 23 and 24. Maps were elaborated using Geographic Information System software QGIS and data from Google Earth Imagery (2022), obtained by installing the XYZ file of the QGIS plugin 'Google Satellite'.

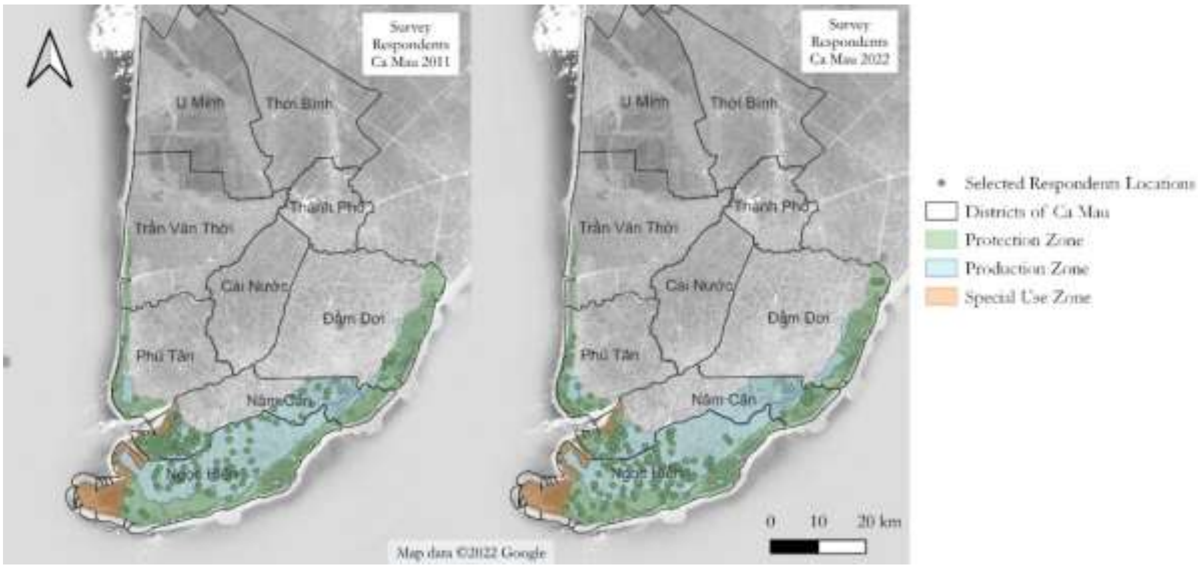


Figure 23 Respondents in production and protection zone in 2011 and 2022 in Ca Mau Province

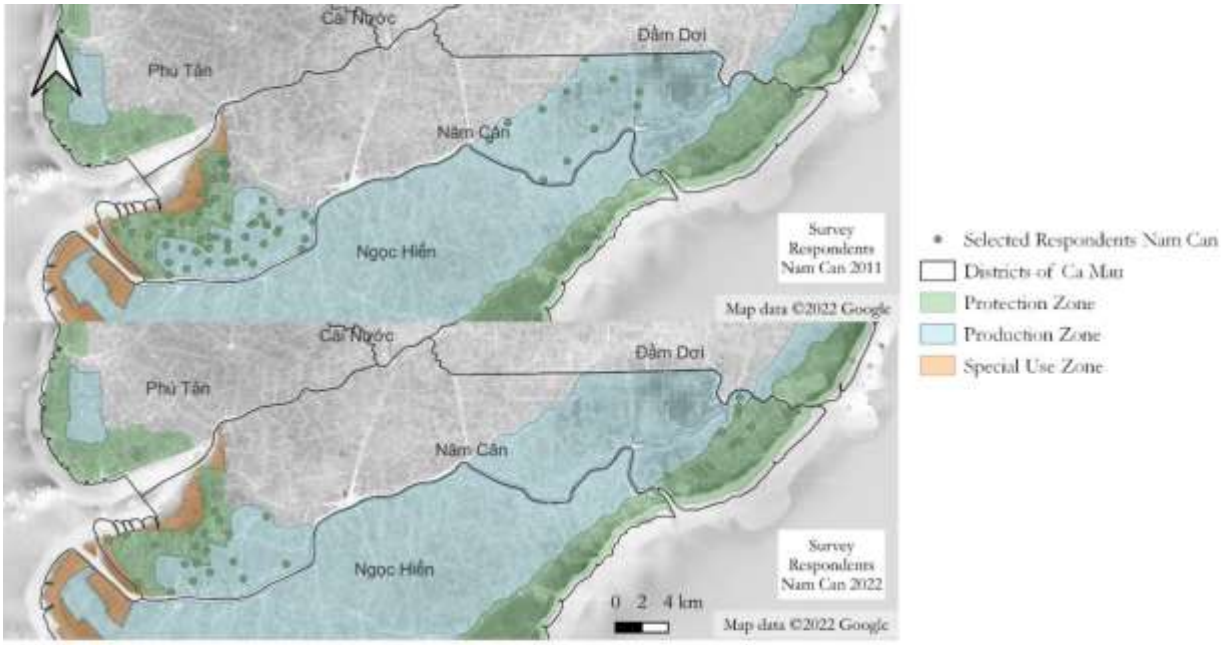


Figure 24 Respondents in production and protection zone in 2011 and 2022 in Nam Can District

4.6.2. Question selection

After retrieving the survey data from 2011 and 2022, relevant questions were selected. This ensured that the analysis focused on the most important variables related to the research objective(s). It helped to eliminate noise and irrelevant data and improve the quality of the results. The questions were selected by their provision of valuable insights into the farmers' perceptions of mangroves, the economic impact of aquaculture and wood exploitation, and their understanding of the Laws and regulations on mangrove wood exploitation. The analysis of the responses helped identify gaps and challenges in current forest management practices and guide policy decisions to ensure the long-term health and sustainability of forests. The selected questions were coded with a fitting acronym to simplify the RStudio code analysis. After importing the spreadsheets into RStudio, the empty cells are converted to no data cells. The 'do not know' and no data rows are removed for each survey question analysis as they do not improve the data quality (Vannette &

Krosnick, 2014) (see Appendix G for a general survey analysis code in RStudio). The sections below illustrate the justification of four selected questions.

Do you care about mangroves?
Mangroves are important ecosystems that provide a variety of services, including coastal protection, carbon sequestration, and biodiversity preservation. However, previous research has shown that farmers in Vietnam do not care about mangroves because they provide low revenue due to taxes, and they do not prioritize the quality of the mangrove trees (Ha et al., 2012b). This lack of care can negatively impact the successful restoration of mangrove forests, which requires replanting and recreation of a healthy and functioning ecosystem.

The Ministry of Natural Resources and Environment explained that Vietnam's National Biodiversity Strategy (2020-2030) acknowledges the importance of using indigenous knowledge to preserve biological resources on a national scale (MONRE, 2013). Research from the Millennium Ecosystem Assessment (MEA), as well as other research supported this approach and demonstrated that a farmer's level of indigenous knowledge, such as knowledge on how to take care of mangroves, can aid in successful restoration efforts (Bosma et al., 2014; Chan et al., 2012; Daniel et al., 2012; MEA, 2005; Spalding & Lael, 2021). Furthermore, research has shown that the more care farmers take in maintaining and harvesting mangroves, the higher their income from the wood (Ha et al., 2012a, 2012b). This highlights the importance of incentivizing farmers to care for mangroves, as it can benefit the ecosystem and their livelihoods. Overall, enhancing knowledge about the importance of caring for mangroves can aid in restoring these crucial ecosystems in Vietnam. This contributes to the wicked problem framework, where complex environmental issues require a multidisciplinary and collaborative approach to find effective solutions (Georgiadou & Reckien, 2018). Researchers can address the challenges of restoring and preserving these important ecosystems by incorporating indigenous knowledge and incentivising care for mangroves.

Do you benefit more of aquaculture or mangrove exploitation, or both?
Literature review showed that economic incentives are one of the biggest reasons for the lack of mangrove implementation on-farm. Analysis of the answers to this question can aid the understanding of mangrove implementation on-farm of the respondents in the different mangrove forest management zones. By exploring the benefits and trade-offs of aquaculture and mangrove exploitation, this research can help shed light on some of the complex interrelationships between economic development, ecosystem conservation, and social well-being in coastal areas.

Do you think mangrove logging for construction/fuel wood is legal?
The literature review showed that construction wood logging is legal to a maximum of $10m^3$ per unit area per three years, and that fuel wood logging is illegal. Analysis of the answers to this question can show insight into the respondents' awareness and knowledge of the current legislation in the different mangrove forest management zones.

4.6.3. Statistical Analysis

Statistical analysis was performed on the selected questions. The analyses aimed to determine whether there was a significant difference between the answers given in the different forest management zones. The data was first analysed on the entire Ca Mau Province level, and consequently on the extracted level of Nam Can District. The results can show insight into whether the mean of the response of the production and protection zone changed between 2011 and 2022, as well as within the protection and production zone. All statistical tests are performed using R-Studio. Depending on the (size of the) dataset, either chi-square tests of independence or Fisher's exact test were utilized. The selection of these tests was dependent on the specific data used and is elaborated further in the Results. The chi-square test is a statistical method employed to assess if there is a significant correlation between two categorical variables. The assumptions necessary for the chi-square test of independence are independence of observations, a minimum sample size of five, nominal or ordinal data, random sampling, an expected value of at least 1 in each cell, and no more than 20% of cells having expected frequencies less than five. Fisher's exact test analyses contingency tables to determine the significant association between two categorical variables, particularly when expected cell counts are low, under the assumptions of independence of observations, nominal data, small sample size with one or more expected cell counts less than 5, and random sampling.

5. RESULTS

In the sections below, the research objectives and subquestions are discussed, according to the methods described, divided into the following Sections: 5.1 policies: comparison of zones and policy levels, 5.2 mapping mangrove coverage on-farms: comparison between policy zones over time (2011 & 2019), 5.3 mangrove coverage: comparing legislation with the remote sensing-based mangrove cover estimates and the farmers estimated mangroves on-farm and lastly, 5.4 farmers perceptions: comparison of survey results between policy zones.

5.1. Policies: comparison of zones and policy levels

RO1: To determine the differences and similarities between mangrove forest-related legal instruments related to mangrove cover in the different forest management zones in Ca Mau

RQ1.a: What are the legal instruments enacted for mangrove cover management in the different forest management zones in Ca Mau?

RQ1.b: What is the current monitoring system for mangrove cover management in the different forest management zones in Ca Mau?

The following sections contain the results of the thorough policy literature-review, focusing on national-level legislation and Ca Mau Province legislation. These sections focus on the differences between the mangrove forest management zones regarding their mangrove management and shrimp farming management on-farm. However, the sections do not further touch the additional implementations of eco-certification, PFES and REDD+, as well as the economic/buffer/full protection zones of Decision 116/QD-TTg[66], which overlap with the legislation of the different forest mangrove management zones and complicate farmers' obligations of mangrove management on-farm.

5.1.1. Legal instruments on mangrove cover and aquacultural obligations

This research found that literature and policies interchangeably use terms like mangrove-to-pond ratio and mangrove cover (percentage) on-farm. E.g. with the national Decision, the (translated) document uses percentages to describe mangrove cover obligations on-farm, whilst literature that writes about this Decision uses both mangrove cover percentage on-farm and mangrove-to-pond ratios to describe the mangrove cover obligations on-farm. However, these terminologies imply different things, as on-farm, there are also dykes, maybe even small parcels with fruit trees and buildings. For example, a mangrove-to-pond ratio of 60:40 contains less mangrove area than a farm with 60% mangrove coverage; see Table 10 below. This research uses mangrove coverage (%) when referring to its results.

[66] Quyết định của thủ tướng chính phủ việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoratoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

Table 10 Explanation of the difference between mangrove coverage on-farm and mangrove-to-pond ratio

	Example	Explanation
Mangrove-to-pond ratio	60:40	The pond should have 60% of its area covered by mangroves, excluding dikes, houses, and other vegetation or structures.
Mangrove coverage (%) on-farm	60%	The farm boundary should have 60% of its area covered by mangroves, while the remaining 40% can be allocated to ponds, dikes, houses, and other vegetation or structures.

As briefly mentioned in the Introduction, National Decision 178/QD-TTg[67], enacted in 2001, describes the obligations regarding mangrove-shrimp management in Vietnam's different forest management zones. According to this Decision, benefits of production forests allocated to households or individuals by the state include state funding for investment, intercropping permission, and collecting rights of non-timber forest products. This Decision stipulates that timber revenues vary from 75% to 100% depending on the investment source (planted or natural forest). This Decision encourages all economic and private sectors involved in forest protection, development, production, and market. In addition, households that contract with forestry companies and management boards in mangrove areas have specific rights and responsibilities. These include receiving government investment funds for planting and protection towards 70% of mangroves on-farm. Moreover, households are entitled to 80-90% of income after tax if they receive financial support from the government or 100% if they invest in their protection efforts without governmental support.

The Decision describes that for protection forests, it is not allowed to cut more than 20% of the forested area during any one period; the harvested area must be replanted, and further harvesting cannot occur until the replanted area is at least three years old. Thus, farmers may cut all forest, but only in a rotation scheme of three years, where there is no more than 20% cut at once and always 60% of mangrove cover left on-farm after thinning. For production forests, the Decision does not seem to stipulate a maximum logging amount; farmers do not have to comply with the 20% logging restriction, i.e. 100% of the forest can be cut as long as it is immediately replanted. This Decision also provides guidelines for provincial governments of implementation.

As a response to this national policy, Ca Mau introduced a provincial Decision 24/QD-UB in 2002, requiring mangrove to pond ratio of 50:50, 60:40 or 70:30 of the total area of farms having less than 3 ha, 3–5 ha, or more than 5 ha, respectively (Baumgartner et al., 2016). Note the use of 'ratio' here[68]. This Decision reformed the structure and management regimes of forest and forestry in Ca Mau, which converted the use-right contracts from green to red certificates. The Decision allows farmers to benefit more from timber marketing and to dredge or excavate the ponds using machines. This Decision significantly differed from the national policy; instead of a mangrove-to-pond ratio of 70:30, Ca Mau implemented a 60:40 ratio. Additionally, Ca Mau has a lower benefit-sharing percentage than the National Policy and determined the amount based on the years of mangrove conservation: 11 years equals 66% and 15 years 95%, while the remaining is for forestry companies and management boards. Many farmers cleared out their ponds to above 40 percent or have not been allocated a farm with 60% coverage (Baumgartner et

[67] Quyết định về quyền hưởng lợi, nghĩa vụ của hộ gia đình, cá nhân được giao, được thuê, nhận khoán rừng và đất lâm nghiệp Hien [Decision on the benefits and obligations of households and individuals assigned, leased or contracted, No. 178/QD-TTg (Nov. 12, 2001)

68 Verification of the terminology in the original Decision 24/QD-UB of Ca Mau is not possible because this Decision could not be obtained.

al., 2016; McEwin & McNally, 2014). Note how both terminologies are used interchangeably in the literature.

Decision 24/QD-UB of Ca Mau was amended by Decision 19/QD-UBND[69] in 2010. This Decision could be obtained directly, stipulating that mangroves should cover at least 60% of the allocated area to the farmers. This provincial Decision gave farmers more control over forest management by transferring contract-based forestry to long-term land use rights for households to benefit farmers from mangrove and shrimp production. It also recognized farmers' authority over forest products. It provides flexible aquaculture regimes by reducing the ratio of mangroves to water in small-size farms, accepting machinery for excavation, and providing equal benefit sharing for farmers from Forest Companies' mangrove logging. However, implementation was slow and problematic (Ha, 2012a).

The exact implementation of legal instruments enacted for mangrove cover management in the different forest management zones is not explained as elaborate for Ca Mau in Decision 19/QD-UBND as the information available in the National Decision (178/2001/QD-TTg[70]). In this provincial Decision, 60% of mangrove cover seems to uphold shrimp farms in both the production and protection zone. Table 11 below provides an overview of all specific obligations regarding mangrove-shrimp management in the different forest management zones (on the national level). The table shows that even on the national level, the obligations and requirements of mangrove farming are not mentioned in the Decision (indicated with a '?'), likely because this is up for implementation by Provinces themselves.

[69] Nhân dân tỉnh Cà Mau ban hành [Decision on the implementation of some forest protection and development policies in Ca Mau Province] No. 19/QD-UBND (Sep. 22, 2010)
[70] Quyết định về quyền hưởng lợi, nghĩa vụ của hộ gia đình, cá nhân được giao, được thuê, nhận khoán rừng và đất lâm nghiệp Hien [Decision on the benefits and obligations of households and individuals assigned, leased or contracted] No. 178/QD-TTg (Nov. 12, 2001)

Table 11 Obligations and regulation of households and individuals per forest management zone, and assigned, leased, or contracted forests and forestry land according to Articles (Art.) in Decision No. 178/2001/DQ-TTg. * Exploitation standards as approved by the Province

				Specific regulations		
	Forest management zones	**Purpose**	**Art.**	**Forest thinning (%)**	**Mangrove logging (%/ha)**	**Aquaculture (%)**
Assigned	special use forest	management, protection, and building up	4	prohibited	prohibited	prohibited
	protection forests	management, protection, and regeneration zoning off	5	?	Max 20%	?
		forestry land without forests but falling under the protection forest planning	6	60% after thinning	Max 20%, freely exploit dead timber	Max 20% of assigned forestry land
	production forest	natural forests subject to production forest planning*	7	?	Only for construction, max 10 m^3 per unit area per 3 years	?
		production forests being planted forests financed by the State budget*	8	?	Only for construction, max 10 m^3 per unit area per 3 years	?
		forestry land without forests but falling under the production forest planning	9	?	No maximum	Max 20% of assigned land area
Leased	production forest	forestry land without forests but falling under the production forest planning for afforestation	10	?	No maximum	Max 20% of leased land without forestry
	special-use /protection forest	dealing in scenic places, tourism, or rest and recreation under the forest canopy	11	prohibited	prohibited	prohibited
Contracted	special use forest	to plant, protect and regeneration- zone off	13	prohibited	prohibited	prohibited
	protection forests	to protect and regeneration-zone off natural forests in the headwater protection areas	14	60% after thinning	Max 20%, freely exploit dry dead timber trees	?
		to plant, tend and protect headwater protection forests	15	60% after thinning	Max 20%	Max 20% of forestry land

Table 11 (continued)

Contracted	protection forests	to plant and protect wind- or sand-shielding protection forests*	16	?	Max 10% per year of area already planted with forests	?
		to plant, tend and protect protection forests in submerged forest areas*	17	?	Max 20%	Max 30% of contracted land area
	production forest	production forests being natural forests*	18	?	?	?
		to restore natural forests being production forests by applying the method of zoning off forests for regeneration combined with additional planting*	19	?	?	?
		to plant, tend and protect production forests*	20	?	?	?

5.1.2. Current monitoring system

In Vietnam, the Ministry of Agriculture and Rural Development (MARD) and the Ministry of Natural Resources and Environment (MONRE) oversee the protection and development of mangrove forests at the national level. At the provincial level, the Provincial People Committees, led by their chairpersons, are responsible for forest management (Pham et al., 2012). MARD has the ultimate responsibility for forest planning and monitoring changes in forest conditions (Tan, 2005). The government established the Vietnam Administration of Forestry to advise the Prime Minister on forest management strategies and operate under the management of MARD. This administration is responsible for forestry planning and monitoring through the Forest Inventory and Planning Institute and the Forest Protection Department.

The planning and monitoring are carried out at various scales, including national, provincial, and local levels, depending on each program's specific objectives and requirements. The national level focuses on developing policies and strategies based on the data collected through remote sensing and ground surveys. The provincial and local levels focus on implementing these policies and strategies and monitoring and reporting on forest conditions and management activities. Forest rangers and community members conduct forest monitoring at the communal or local level, who use ground surveys to monitor forest cover and disturbance. The variables monitored include forest cover, forest types, species composition, forest health, and carbon storage (Coi et al., 2011).

The Forest Inventory and Planning Institute operates mostly on national and provincial levels, while the Forest Protection Department operates on the Province, district, community, and village levels (Höyhtyä et al., 2013; Phat, 2008). The Forest Inventory and Planning Institute conducts the National Forest Inventory, Monitoring, and Assessment Program every five years (Trieu et al., 2020). The National Forest Assessment of Vietnam is a pilot part of a global programme, “Sustainable Forest Management in Changing Climate”, launched by FAO from 2011 to 2014 (Höyhtyä et al., 2013). The National Forest Inventory aims to retrieve information on the nationwide area of forests, volume and quality of the forests and potential forest lands. This inventory uses SPOT 5 and 6 imageries and field sampling plots to prepare thematic maps in scales of 1:10.000 for communes, 1:50.000 for districts and 1:100.000 for Provinces. Variables include forest function, forest origin, owner type, soil condition and contract situation (red book) (Silfverberg et al., 2015). Whether similar projects are still executed by the Forest Inventory and Planning Institute after 2014 remains unclear.

Minimal data exchange between the Forest Inventory and Planning Institute and the Forest Protection Department results in redundant efforts, increased expenses, and inconsistencies in their outputs (Tan, 2005). The Forest Protection Department and its branch offices at the provincial and district levels use the Forest Inventory and Planning Institute's data to prepare annual monitoring reports on forest loss and new forest plantations. These reports are compiled into annual national forest cover statistics known as R-PINs (Phat, 2008; Pham et al., 2012).

The General Department of Land Administration of the Ministry of Natural Resources and Environment is in charge of land administration, including forest land use planning, registration, allocation, monitoring, and inspection to ensure compliance with relevant Laws and regulations. The General Department of Land Administration conducts land use inventories every five years based on the National Land Registration System and ground surveys. The variables monitored by the General Department of Land Administration include forestland use, cover, tenure, ownership, and changes. The scale at which these inventories are conducted is national, covering all Provinces and districts in Vietnam (Pham et al., 2012).

However, inconsistencies are created by using different land use categories and available forest data between the General Department of Land Administration and the Forest Protection Department. While both provide information on the total area of the three types of forest management, they differ in their identification of 'unused land', which is categorized as 'bare land, mountain without forest' by the General Department of Land Administration and as 'forest land without forest' by the Forest Protection Department (Pham et al., 2012) (see Appendix H Figure 49).

Monitoring the coverage of mangrove forests is an essential aspect of forest management in Vietnam, and as it is apparently complex, various new monitoring systems have been established with the support of international organizations such as USAID, CIFOR, and GIZ. One such system is the Forest Monitoring System, which automatically connects satellite images to a forest change detection tool and integrates data on boundaries, planning around three types of forest and forest status, and can monitor forest changes visually and easily. Part of this system, is the Forestry Sector Monitoring Information System (FORMIS[71]) platform, set up by the Vietnam Forest Development Strategy of 2006(-2020), which allows the forest resource database to be integrated with the national forest inventory results and updated data on forest change, REDD+ and PFES (Trieu et al., 2020). FORMIS uses various (unknown) economic, social and environmental indicators and uses FIPI's data as a baseline (Silfverberg et al., 2015). Monitoring for PFES and eco-certification is based on individual landowner reports and unannounced monitoring visits (Baumgartner & Nguyen, 2017).

In Vietnam, District-level and Commune People's Committees are responsible for forest protection and development in their respective areas. They appoint forest staff members to monitor forestry activities. However, due to budget constraints, many communes cannot afford to hire forest staff. Village leaders act as intermediaries between national Laws and customary practices in an informal system below the commune level. The success of reforestation programs depends on the involvement of these village leaders (Pham et al., 2012). Additional scientific research and armed force units are also involved in monitoring and enforcing forest management regulations in Ca Mau (No. 25/2004/L-CTN[72]). However, the details of how these

[71] FORMIS Phase I (2009-2013) build the base system for integration, Phase II (2013-2018): aimed to integrate more extensive data from FIPI, whilst supporting VNFOREST to develop software on monitoring changes in forest and forestry land.
[72] Luật bảo vệ và phát triển rừng [Law on forest protection and development], No. 25/L-CTN (Dec. 14, 2004)

efforts operate specifically in Ca Mau Province remain uncertain. There is a lack of interaction with the Forestry Service, which should be in charge of intensive monitoring of mangrove forest conditions in the area. Management of mangrove forests in coastal villages has been mostly carried out collectively by local communities (Suharti et al., 2021).

In conclusion, while there have been efforts to establish monitoring systems for mangrove forests in Vietnam, there are still challenges to effective monitoring and enforcement. In Vietnam, the forest monitoring system reflects the current jurisdictional system, with different parties performing forest cover analysis independently and overlapping responsibilities. Similar institutional names[73] and inconsistent use thereof cause additional complexity[74]. Further research and development of monitoring mechanisms are necessary to ensure the sustainable management of these important ecosystems; see Figure 25 below for the final overview of the monitoring in Vietnam.

[73] The understanding of the current monitoring system is complicated, as different terms and acronyms are used in literature, which is confusing interpretation, such as;
- DoFP (Department of Forest Protection) (Pham et al., 2012; Yasmi et al., 2017)
- FPD (Forest Protection Department) (Dang, 2022; Phat, 2008), or as 'Forest Protection sub-Department' (Pham et al., 2019)
- DoF (Department of Forestry) (Pham et al., 2012) versus GDOF General Department of Forestry (Pham et al., 2012)
- DOF (Department of Fisheries) (Christensen et al., 2008) or (Department of Forestry) (Phat, 2008)

[74] In this research it is assumed that GDOF, DOF/DoF in literature refers to Department of Forestry or Forestry Department and is the same.

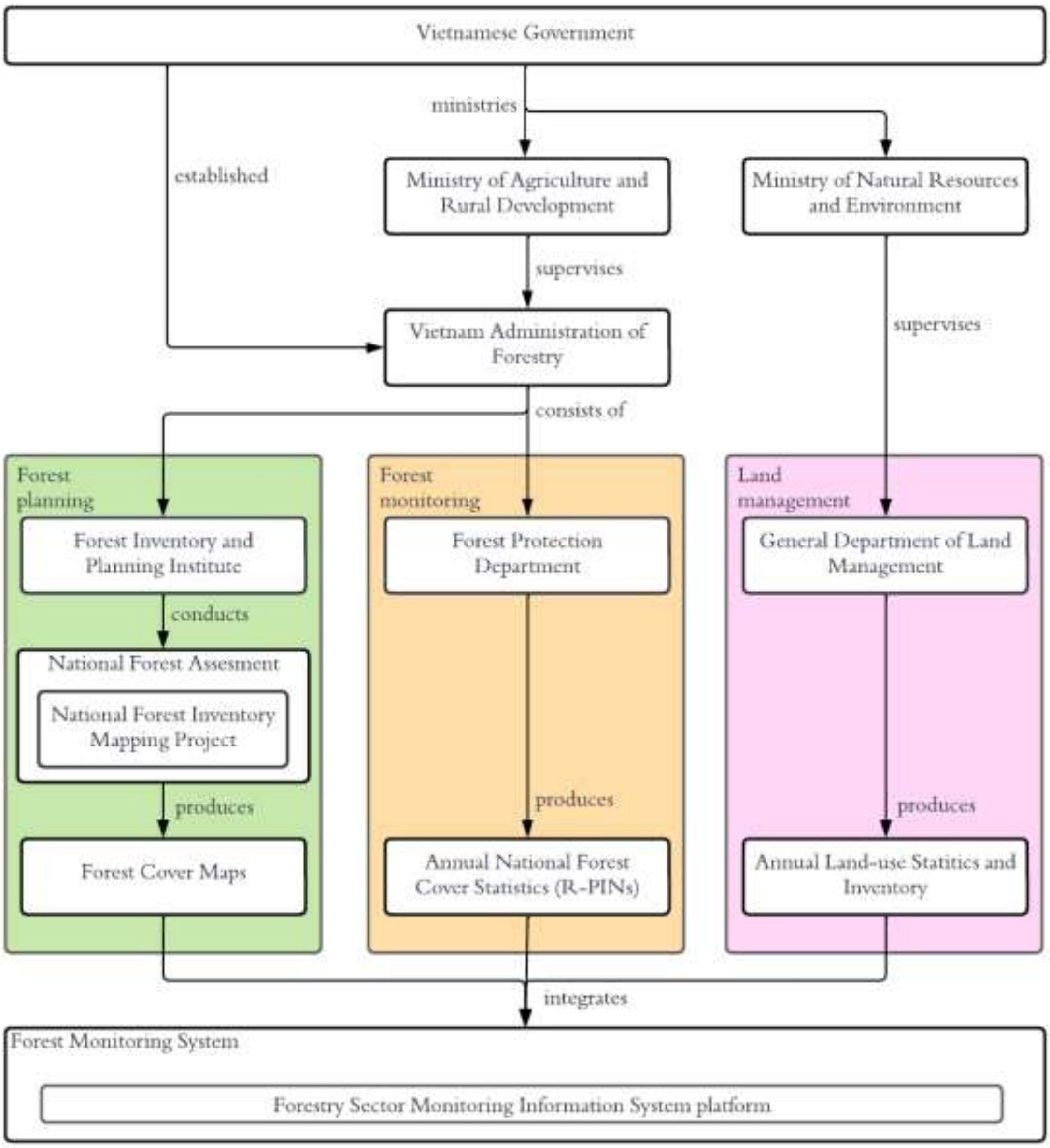


Figure 25 Mangrove forest monitoring Vietnam. Arrows indicate the relationships between boxes. Colors chosen to enhance the distinction between forest planning, -monitoring and land management monitoring

5.2. Mapping mangrove coverage on-farm: comparison between policy zones over time in Nam Can District

RO2: To analyse the difference between the forest management zones in their mean mangrove and propagule cover on-farm in Nam Can District 2011 vs. 2019

RQ2.a What was the mean % coverage of mangroves on-farm per forest management zone in the study area (2011)?
RQ2.b What was the mean % coverage of mangroves on-farm per forest management zone in the study area (2019)?
RQ2.c What is the mean % change in mangrove cover on-farm per forest management zone in the study area and how do these differ between the different forest management zones?
RQ2.d How did the different land cover types change over time (2011-2019)?

The following sections present the outcomes of the remote sensing-based delineated mangrove coverages on-farm in 2011 and 2019. Additional in-depth analysis is performed on the propagule cover on-farm. The study also reveals specific land cover type changes between the two images.

5.2.1. Mangrove cover (%) on-farm

Figures 26, 27 and 28 below show the mangrove cover manual delineation results. The exact amounts of mangrove cover and change per shrimp farm are shown in Figure 29 and 30, respectively. Appendix I Table 22 provides an overview of the percentual coverage of all classes per shrimp farm, using green and red to highlight changes >10% (positive/negative). A range of -10% to 10% is possibly due to digitization errors during on-screen tracing of satellite images (Dempsy, 2017). As seen in Figure 29, the mean mangrove percentage in both the production and the protection zone is far below the minimum threshold of eco-certification found in the literature of 50% and 60% by Decision No. 19/QD-UBND[75].

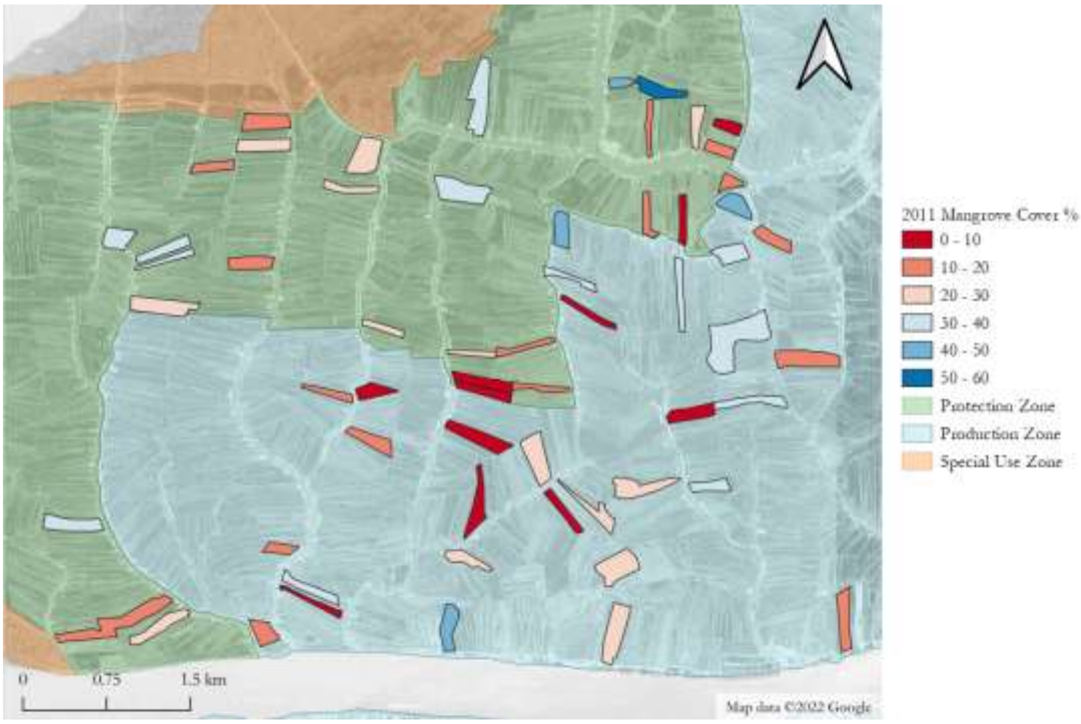


Figure 26 Mean mangrove cover % of randomly selected shrimp farms (n=60) 2011 in Nam Can

[75] Quyết định ban hành quy định về thực hiện chính sách bảo vệ và phát triển rừng trên địa bàn tỉnh Cà Mau do Ủy ban nhân dân tỉnh Cà Mau ban hành [Decision on the implementation of some forest protection and development policies in Ca Mau Province] No. 19/QD-UBND (Sep. 22, 2010)

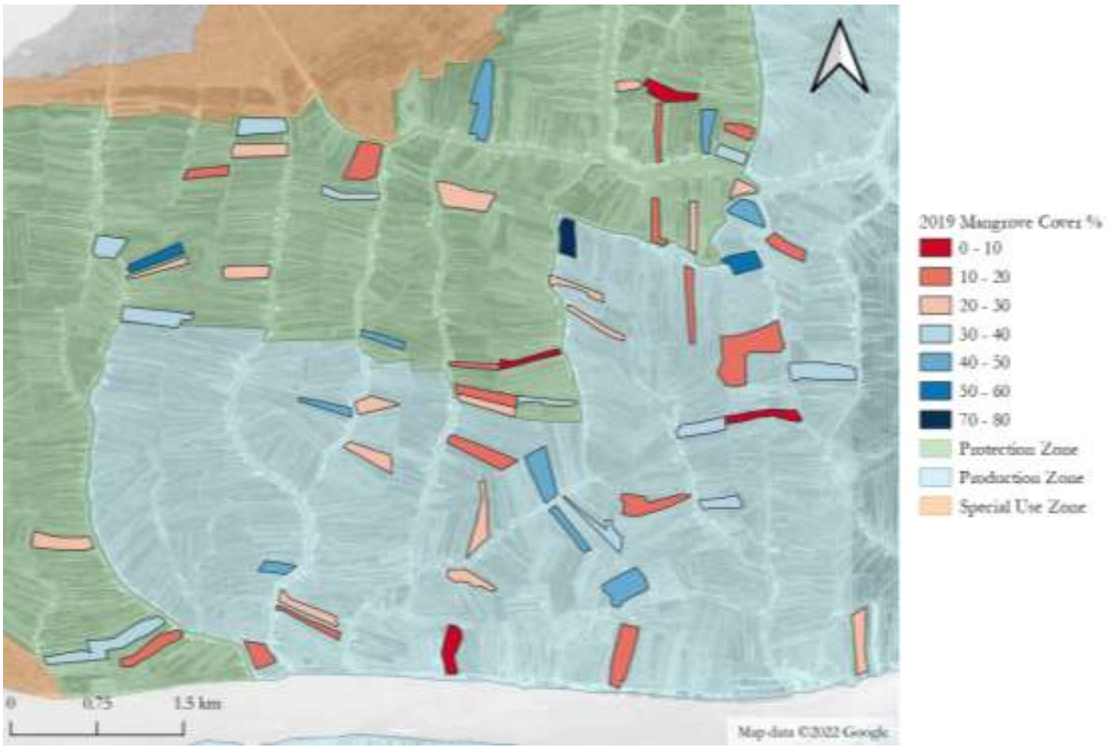


Figure 27 Mean mangrove cover % of randomly selected shrimp farms (n=60) 2019 in Nam Can (note: cover class 60-70% is missing/empty)

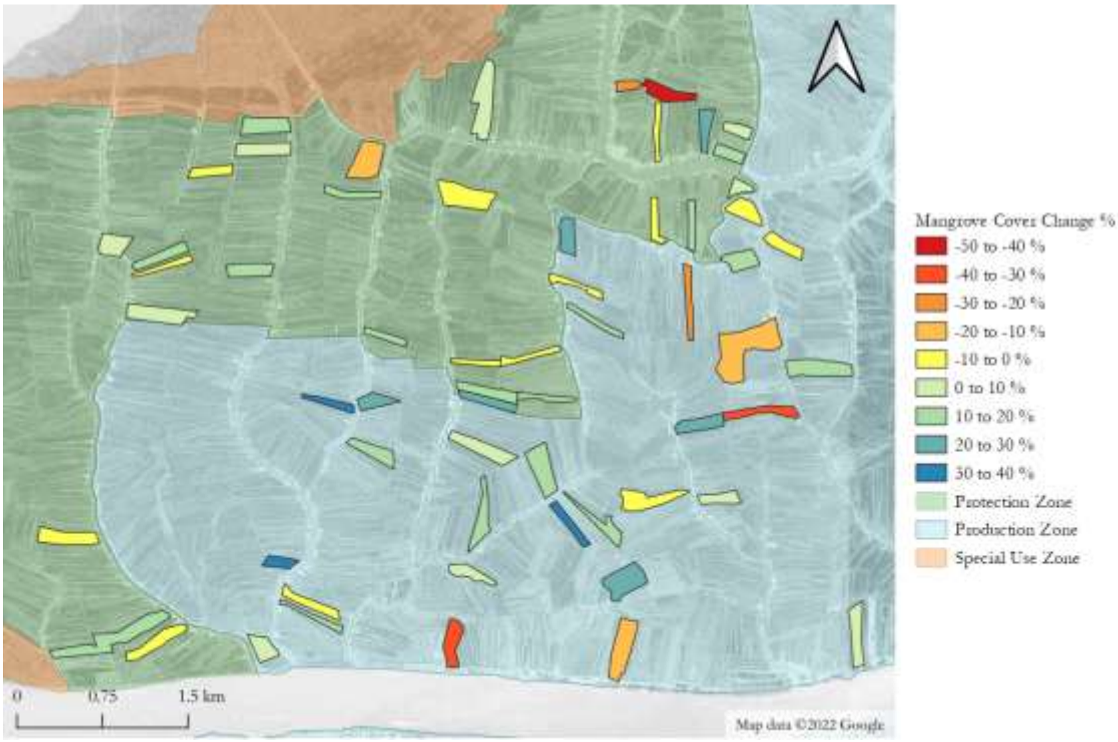


Figure 28 Map of randomly selected shrimp farms with mean mangrove cover % change on-farm in Nam Can (2011-2019)

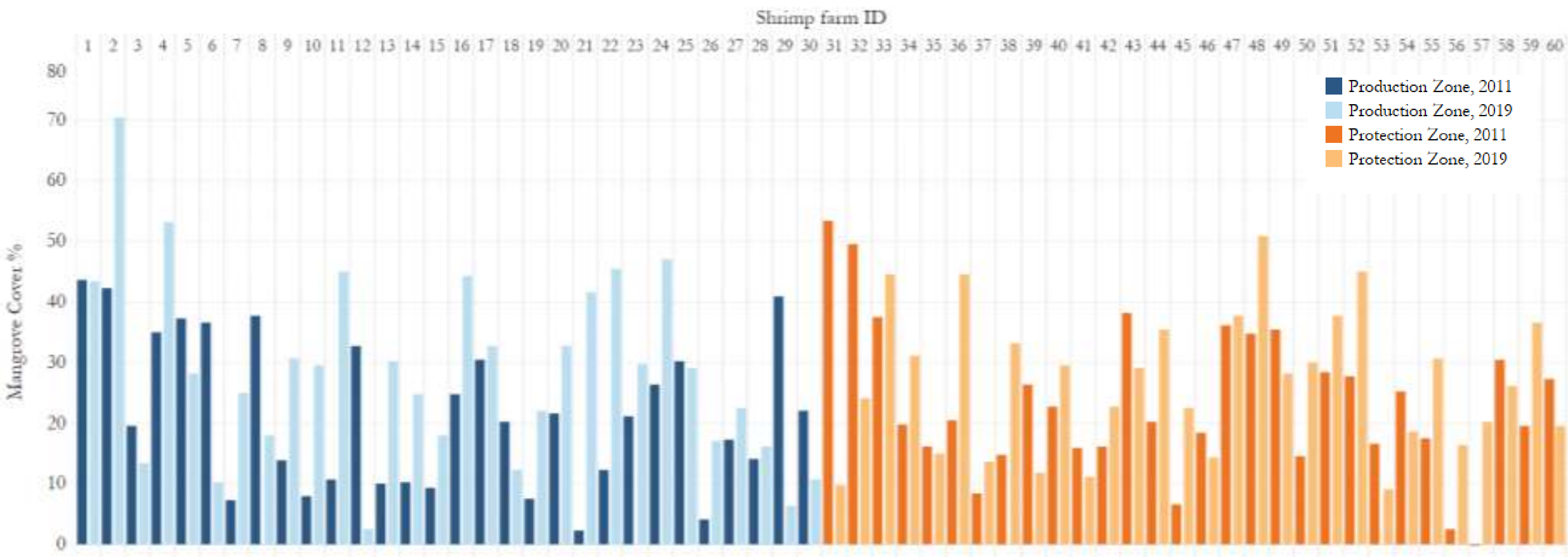


Figure 29 Percentage of mangrove cover in shrimp farms (Shrimp farm ID) across two years (2011 and 2019). Data is categorized into production zone (n=30) and protection zone (n=30).

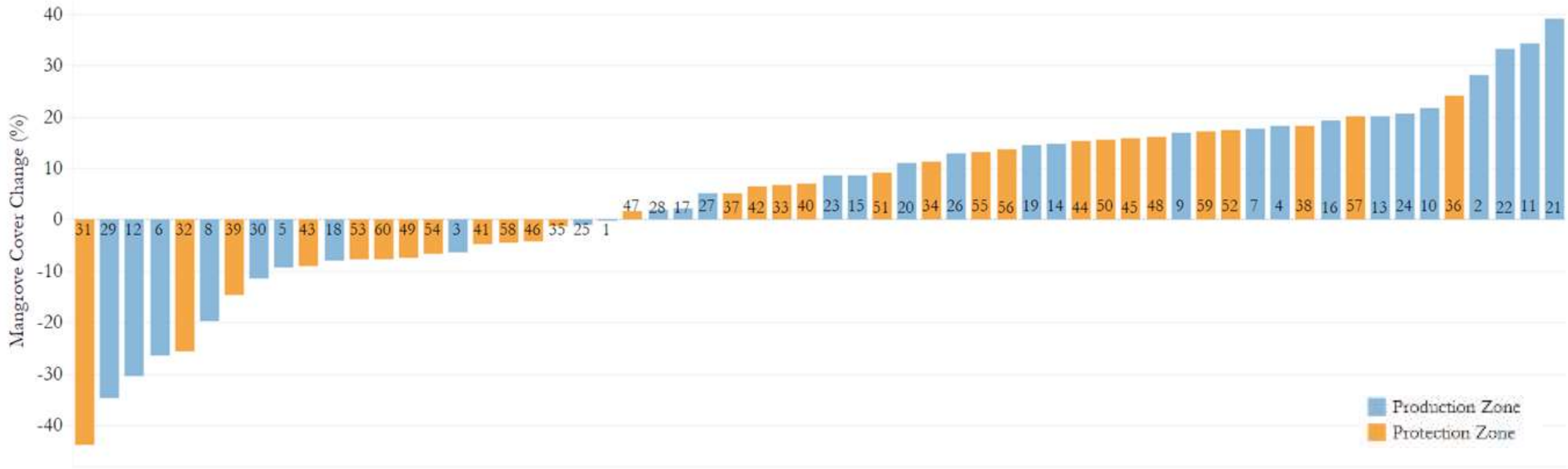


Figure 30 Percentage of change in mangrove cover across different forest management zones (2011, 2019). Data ranges from highest decrease to highest increase and is identified by the shrimp farm ID label

Table 12, presented below, displays the average percentages and standard deviation (SD) of the class coverages in 2011 and 2019 for the production and protection zone, the combined level, and the mean change in the percentage of mangrove cover.

Table 12 Mean class areas (30 farms in the production and 30 in the protection zone) in %; mean (μ) and standard deviation (SD) in Nam Can District. Quickbird 2011 (n=7807; n=151 propagule, n=7656 mangrove) and GeoEye 2019 (n=5975; n=408 propagule, n=5567 mangrove). Statistical significance was computed at the 5% significance level for mangrove and propagule coverage using the two-way mixed ANOVA.

	Class Percentages 2011 (%)						**Class Percentages 2019 (%)**						**Change 2011-2019 (%)**	
	Mangrove		Propagule		Other		Mangrove		Propagule		Other		Mangrove	
	μ	SD	μ	SD	μ	SD	μ	SD	μ	SD	μ	SD	μ	SD
Production zone	21.6	12.5	2.5	4.8	75.9	11.7	28.4	15.4	3.0	6.5	68.8	13.3	+6.8	0.19
Protection zone	23.3	12.5	1.8	5.1	74.9	12.4	26.6	11.6	2.8	6.8	70.6	10.8	+3.3	0.15
Total	22.4	12.5	2.1	4.9	75.4	12.0	27.5	13.6	2.9	6.7	69.6	12.1	+5.0	0.17

The two-way mixed ANOVA showed no significant interaction effect between time and zoning area on mangrove cover ($F(1, 58) = 0.632$, $p > .05$). Post-hoc testing using Bonferroni adjusted p-value showed a significant main effect for time on mangrove cover on-farm ($F(1, 58) = 5.261$, $p < .05$) with a small effect size. No significant main effect for zoning areas ($F(1, 58) = 0.00$, $p > .05$) was computed (see Appendix J Figures 50 to 65 for all statistical tests and outcomes). This test shows that the mangrove cover in 2019 was significantly higher than in 2011 in both the production and the protection zone. However, there was no significant difference between the zones.

The two-way mixed ANOVA showed no significant interaction effect between time and zoning area on propagule cover ($F(1, 58) = 0.054$, $p > 0.05$). Post-hoc testing using the paired Wilcoxon Sign test and the unpaired Mann-Whitney U test showed no significance for the main effects of time and zoning area, respectively ($p>0.05$). This test shows that the propagule area % measured is not significantly different in both mangrove forest management zones in both years.

The areas of the mangrove and propagule polygons were combined to obtain intermediate results on the total class areas within the two zones and on the combined level, which are presented in Table 13 below. These results show an increase in the total mangrove area of 100.000 m^2 between 2011 and 2019.

Table 13 Total area of the classes (in 1000 m^2) in Nam Can District Quickbird 2011 (n=7807) and GeoEye 2019 (n=5975)

	Class area 2011			**Class area 2019**			**Change area 2011-2019**
	Mangrove	Propagule	Other	Mangrove	Propagule	Other	Mangrove
Production zone	337	31	1084	391	45	1016	54
Protection zone	323	19	960	369	43	890	46
Total	660	50	2044	760	88	1906	100

The results of a more in-depth analysis of land cover class changes are presented in the next paragraph. Tables 14 to 16 show how much of the mangrove, propagule and other areas remained the same or was converted to a different class. For example, 48.12% of the mangrove-classified polygons delineated in 2011 were also classified as mangrove polygons in 2019 in the production zone. 6.1% got converted to propagules, and 45.8% to other (pond water, other vegetation or dikes etc.). These tables show limited differences between the production and the protection zone in their respective land cover changes. It would be assumed that production forest has more propagules (due to harvesting and replanting cycles, whereas protection forests have limited rights regarding this matter.

Table 14 Mean percentual land cover change in the production zone in Nam Can

Production zone		2019		
		Mangrove	Propagule	Other
2011	Mangrove	48.1%	6.1%	45.8%
	Propagule	58.3%	1.2%	40.5%
	Other	19.5%	2.2%	78.3%

Table 15 Mean percentual land cover change in the protection zone in Nam Can

Protection zone		2019		
		Mangrove	Propagule	Other
2011	Mangrove	52.3%	8.8%	35.9%
	Propagule	44.2%	0.6%	55.2%
	Other	19.0%	1.5%	79.5%

Table 16 Mean percentual land cover change in the production and protection zone combined in Nam Can

Combined level: production and protection zone		2019		
		Mangrove	Propagule	Other
2011	Mangrove	51.6%	7.4%	41.0%
	Propagule	52.9%	0.9%	46.2%
	Other	19.2%	1.9%	78.9%

5.3. Comparison of mangrove estimates: remote sensing-based versus farmers' estimates

The sections below compare farmers' estimates of mangrove cover on-farm to the remote sensing-based mangrove cover estimates. Additionally, the mangrove coverages are compared to policies regarding mangrove cover on-farm.

RO3: To assess whether the forest policies related to mangrove cover in the different forest management zones are in line with the mangrove cover on-farm

- **RQ3.a** Is there a significant difference in the mean estimated mangrove cover % on-farm in the different forest management zones in Ca Mau and Nam Can in 2011 and 2022?
- **RQ3.b** Is there a significant difference between the averages of the estimated mangrove cover on-farm and the delineated mangrove cover on-farm in 2011 in Nam Can?
- **RQ3.c** Is there a statistically significant correlation between farm size and mangrove cover (change) on-farm in Nam Can (% and area)?
- **RQ3.d** Is there a a statistically significant correlation between distance to open water and mangrove cover on-farm in Ca Mau?

5.3.1. Estimated mangrove cover on-farm

In the survey, the farmers had to estimate their mangrove cover on-farm in 2011 and 2022. First, a comparison is made between the estimated percentages of mangrove cover on-farm in Ca Mau and Nam Can between the production and protection zone. Afterwards, the Nam Can estimates are compared with the manual delineation results.

For the estimated mangrove cover on-farm in the production and protection zone and the total in Ca Mau; see Figure 31 below (see Appendix K Figures 66 to 93 for all general statistics and statistical test outcomes, including and excluding outliers for Ca Mau).

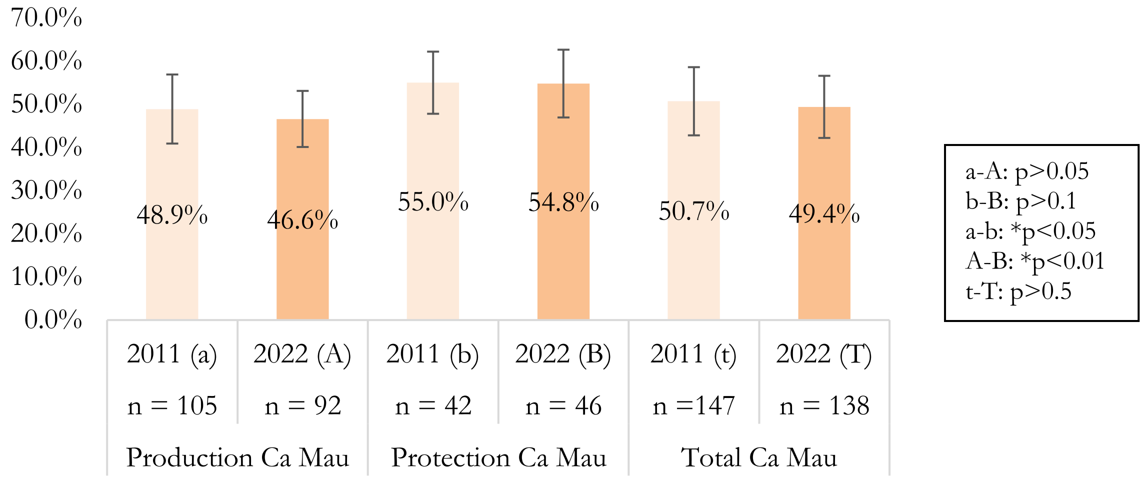


Figure 31 Means and standard deviation of the estimated mangrove cover percentage on-farm in Ca Mau Province. Estimated by farmers in the production (a & A) and protection (b & B) zone, and the mean totals including outliers (t & T). The Mann-Whitney U test was used on all sets of combinations.

The removal of outliers did not increase the significance; it was chosen to keep the outliers in the analysis. The results show a significant difference between the policy zones in mangrove cover estimates in 2011 and 2022 in Ca Mau; farmers in the protection zone estimated their mangrove cover on-farm significantly higher than those in the production zone.

When looking at the mangrove cover estimates in Nam Can District, see Figure 32 below, no significant differences were found (see Appendix K Figures 94 to 118 for all general statistics and statistical test outcomes, including and excluding outliers for Nam Can). The removal of these outliers did not increase the significance; it was chosen to keep them in the analysis. The results show no difference between farmers in Nam Can District located in the production or protection zone in their mangrove cover estimation on-farm in 2011 and 2022.

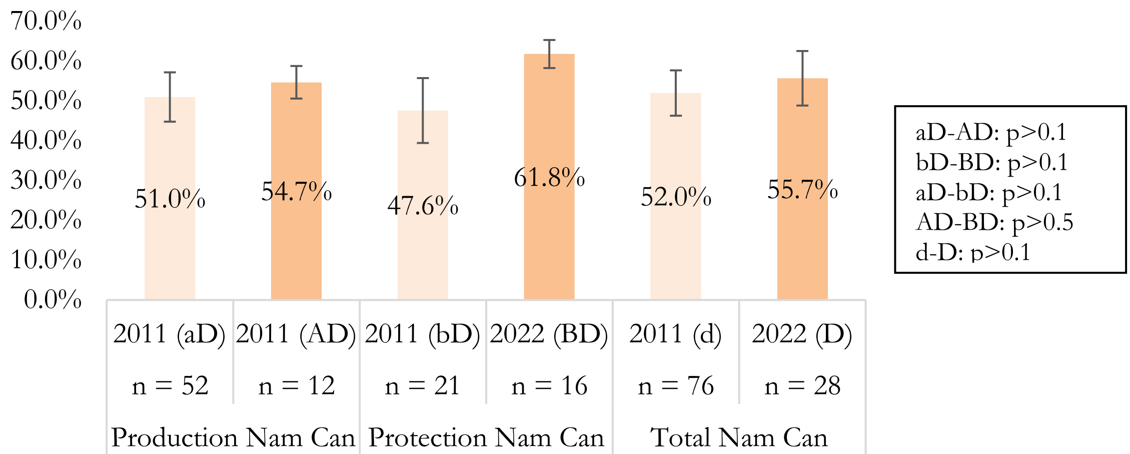


Figure 32 Means and standard deviation of the estimated mangrove cover percentage on-farm in Nam Can District. Estimated by farmers in the production (aD & AD) and protection (bD & BD) zone, and the mean totals (d & D) including outliers. The Mann-Whitney U test was used on all sets of combinations.

5.3.2. Remote sensing-based manually delineated mangrove cover versus estimated mangrove cover on-farm Nam Can

The comparison of the remote sensing-based assessment and the farmer's estimate of mangrove coverage on-farm shows that there is a statistically significant overestimation by the farmers. This holds for both zones; see Figure 33 below (see Appendix K Figures 119 to 125 for all general statistics and statistical test outcomes).

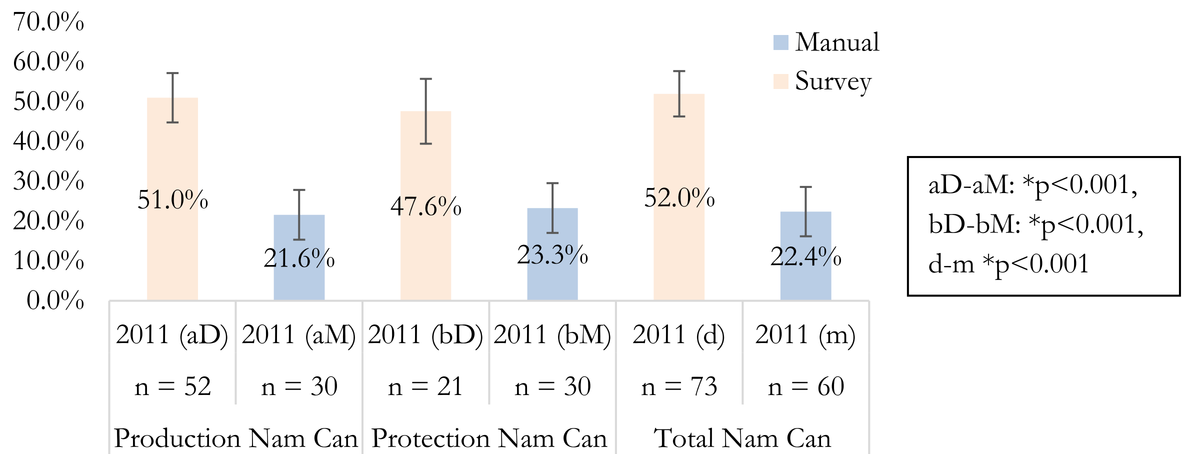


Figure 33 Means and standard deviation of the remote sensing-based manual delineation (indicated with m) and estimated mangrove cover (indicated with d) on-farm in Nam Can in 2011. The Mann-Whitney U test was used on all sets of combinations. The tests have large effect sizes of 0.734, 0.794 and 0.768, respectively.

5.3.3. Correlation remote sensing-based manually delineated mangrove cover (change) (m^2) and shrimp farm area (m^2) Nam Can

Pearsons correlation test is used to assess the correlation between the manually delineated mangrove cover (in % and m^2) and on-farm and the shrimp farm area (see Appendix K Figures 126 to 132 for all general statistics, outliers, and statistical test outcomes). Outliers[76] removed as they significantly affected the regression equation (and Pearson's correlation test is very sensitive to outliers).

Pearson's correlation test showed that the manually delineated mangrove cover percentage and shrimp farm area were not correlated for any combination of the tests; see Table 17 below. Therefore there is no relationship between the size of a shrimp arm and how much percentage of mangroves they have implemented on their farm. Pearson's correlation test did show that the manually delineated mangrove cover area and shrimp farm area were positively correlated on all levels in 2011 and 2019, but not regarding the change; see Table 18 below. The larger the farm area, the more the mangrove area is implemented on-farm.

[76] Outlier detection showed two non-extreme outliers (1.5*IQR) of the shrimp farm area in the protection zone (ID=33, 59) and one extreme outlier (3*IQR) at a shrimp farm in the production zone (ID=8).

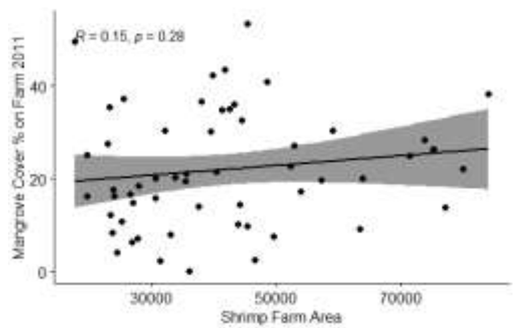
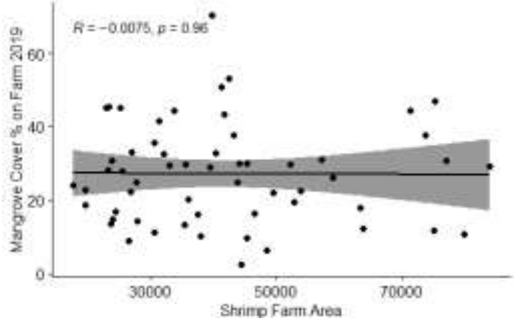
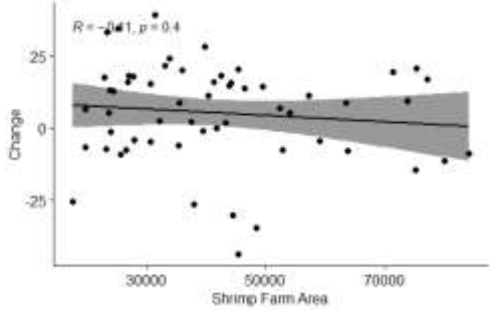
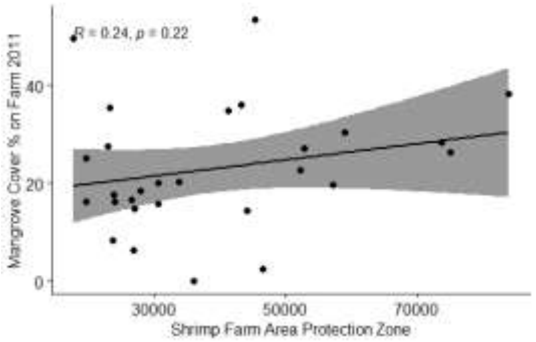
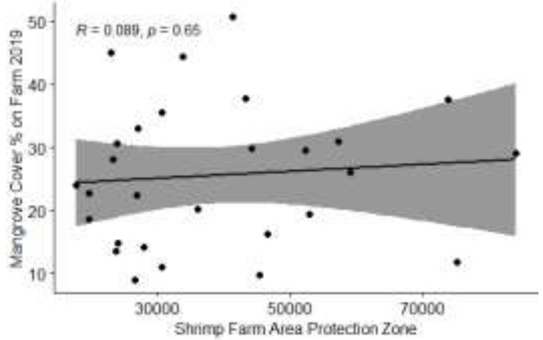
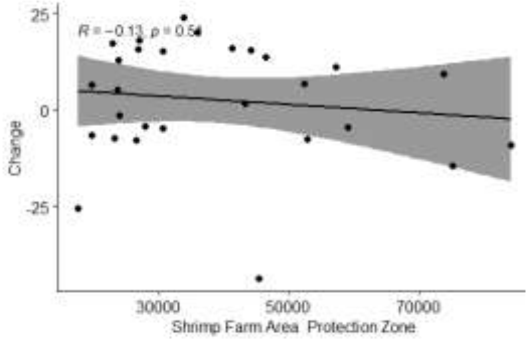
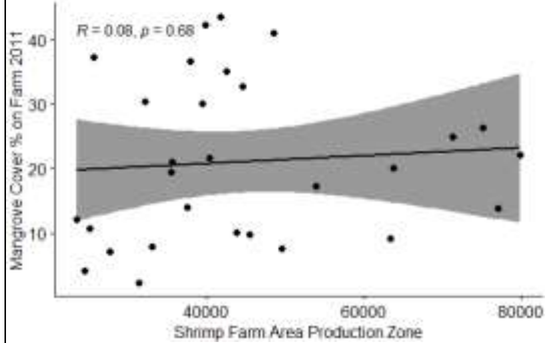
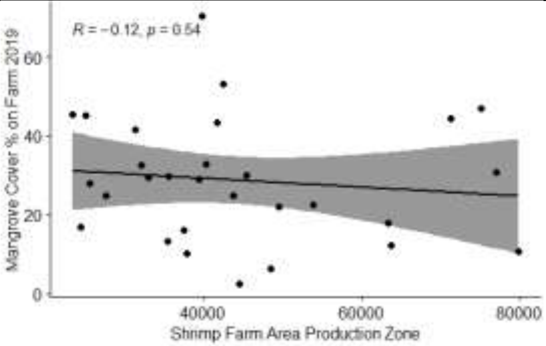
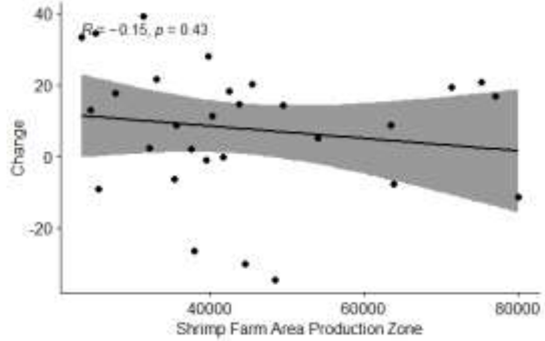
<table>
<tr><th></th><th>2011</th><th>2019</th><th>Change %</th></tr>
<tr><td>Total (Production + Protection Zone) n=57</td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>Protection Zone, n=28</td>
<td></td>
<td></td>
<td></td></tr>
<tr><td>Production Zone, n=29</td>
<td></td>
<td></td>
<td></td></tr>
</table>

Table 17 Results Pearson's correlation test shrimp farm area (m2) and mangrove coverage (%), and change (%) - outliers removed

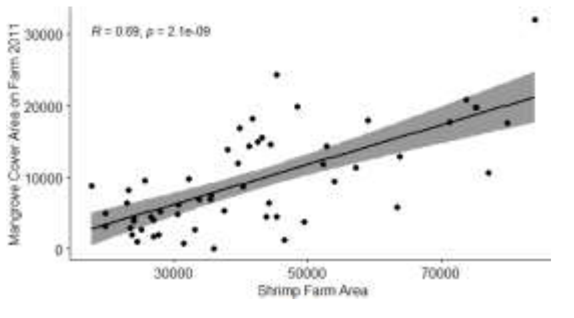
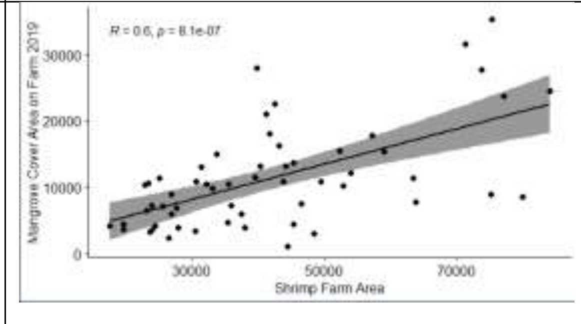
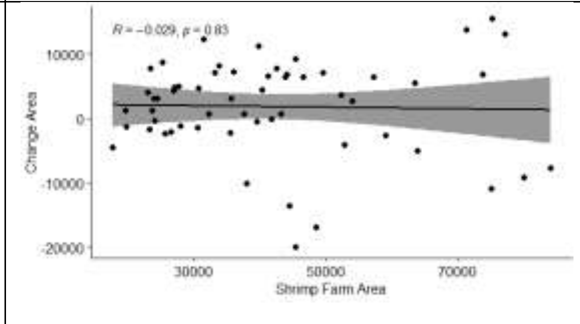
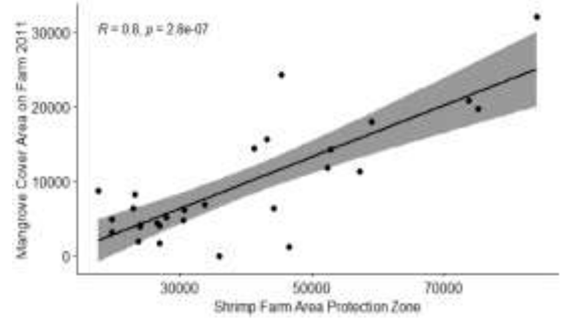
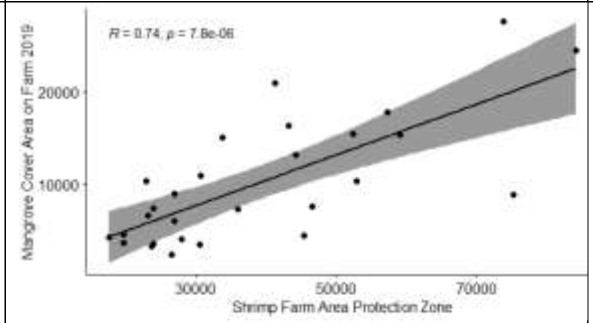
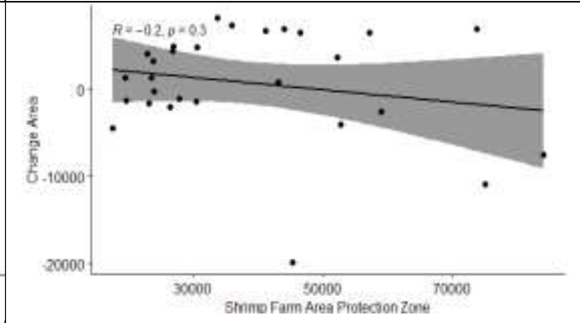
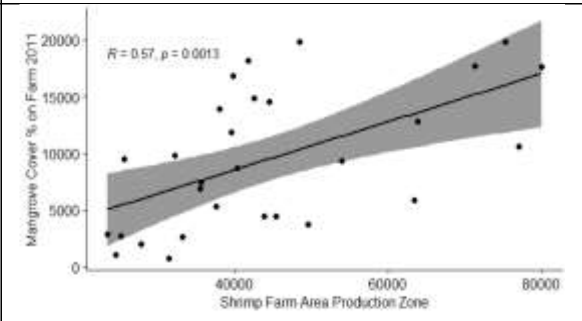
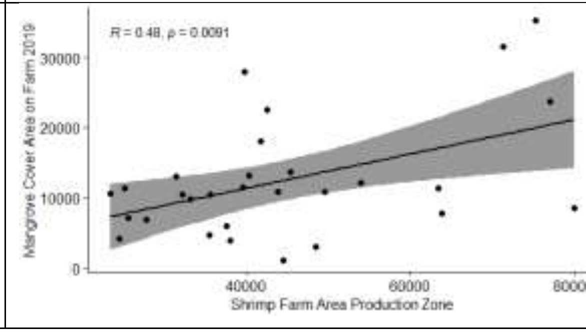
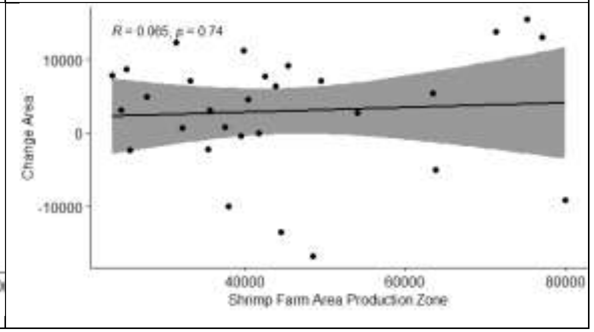
	2011	2019	Change Area
Total (Production + Protection Zone) n=57			
Protection Zone, n=28			
Production Zone, n=29			

Table 18 Results Pearson's correlation test shrimp farm area (m^2) and mangrove coverage (m^2), and change area (m^2) - outliers removed

5.3.4. Distance to open water Ca Mau: estimated mangrove cover

Using the distance to open water, the estimated mangrove cover is categorized into the full protection zone (FPZ), the buffer zone (BZ), and the economic zone (EZ) (see Appendix K Figures 133 to 136 for all general statistics and statistical test outcomes). These categories are (<500m, 500-4000m and >4000m, respectively (adapted from Tran et al., 2015). See Figures 34 and 35 below for the boxplots of the estimated mangrove covers in these zones in 2011 and 2019, respectively. The Kruskal-Wallis chi-squared test with Bonferroni adjusted p-value showed a significant difference between the estimated mangrove cover and their distance to open water in both 2011 and 2022. The post hoc pairwise Wilcoxon comparison, using Bonferroni's adjusted p-value, shows a significant difference between the economic zone and the buffer zone in the estimated mangrove cover on-farm in 2011 and 2022. Policy thresholds indicate mangrove coverage of 60% in the buffer zone and no specific coverage of mangroves in the economic zone. In 2011 and 2022, the median and most estimates in the buffer zone were below 60%. These results thus show that Decision 116/QD-TTg[77], related to these zones, is (probably) not effective.

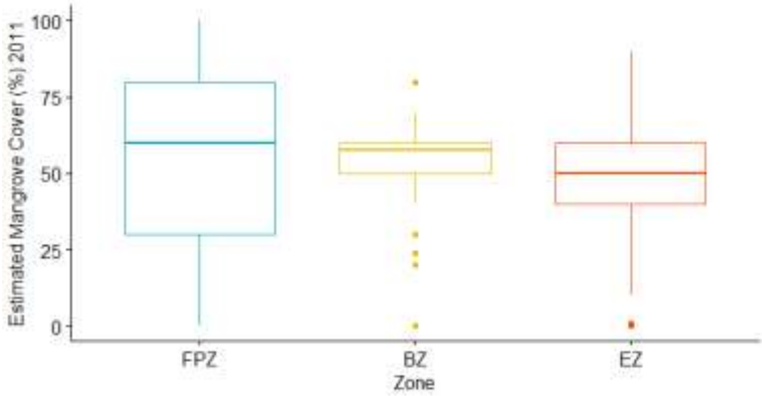


Figure 34 Boxplots of estimated mangrove cover 2011. Categorized in the full protection zone (FPZ), buffer zone (BZ) and economic zone (EZ), based on their distance to open water (<500m, 500-4000m and >4000m, adapted from Tran et al., 2015). The vertical line in the boxplots indicates the median. Bonferroni adjusted p-value showed; χ^2 (2, N = 148) =8.217, p < 0.01

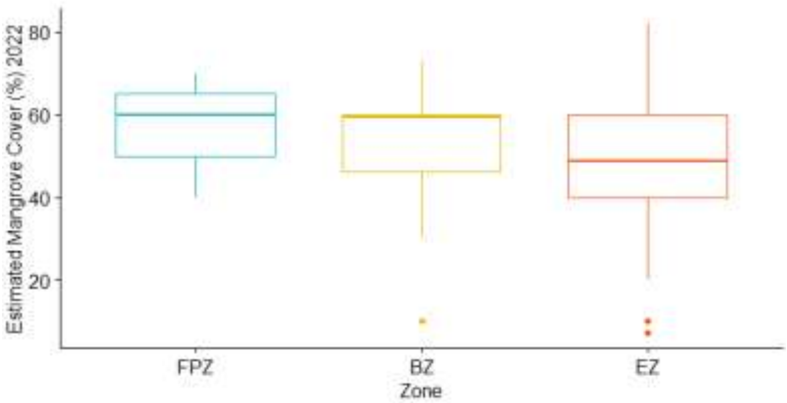


Figure 35 Boxplot of estimated mangrove cover 2022. Categorized in the full protection zone (FPZ), buffer zone (BZ) and economic zone (EZ), based on their distance to open water (<500m, 500-4000m and >4000m, adapted from Tran et al., 2015). The vertical line in the boxplots indicates the median. Bonferroni adjusted p-value showed; χ^2 (2, N = 138) =11.759

[77] Quyết định của thủ tướng chính phủ về việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoratoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

5.4. Farmers' perceptions: comparison of survey results between zones (2011, 2022)

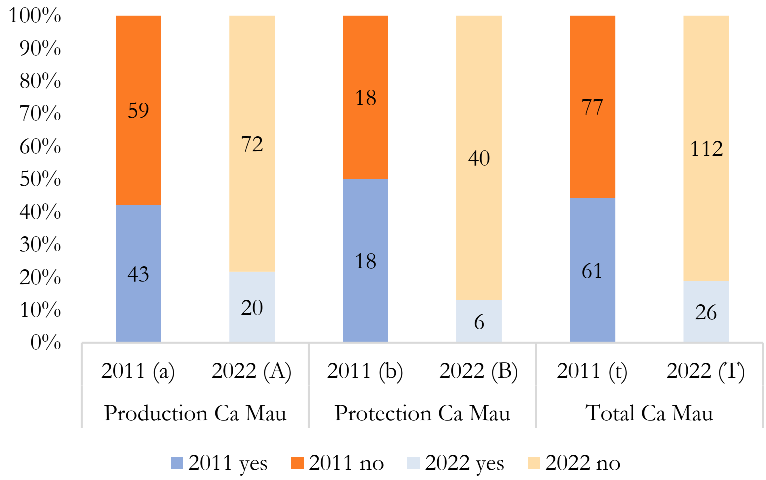
RO4: To analyse motives of shrimp farmers in different forest management zones to maintain or change their mangrove cover on-farm in Nam Can District and Ca Mau Province

- **RQ4.a** To what extent is there a difference between the forest management zones in whether farmers care about mangroves, on the level of Ca Mau Province and Nam Can District?
- **RQ4.b** To what extent is there a difference between the forest management zones in the benefits for farmers in mangrove exploitation and aquaculture, on the level of Ca Mau Province and Nam Can District?
- **RQ4.c** To what extent is there a difference between the forest management zones in farmers' beliefs regarding the legality of mangrove logging for construction wood, on the level of Ca Mau Province and Nam Can District?
- **RQ4.d** To what extent is there a difference between the forest management zones in farmers' beliefs regarding the legality of mangrove logging for fuel wood, on the level of Ca Mau Province and Nam Can District?

The following sections provide a detailed description of the survey analysis results concerning farmers' perceptions. These sections aim to better understand the factors that drive farmers to manage mangrove cover on their farms.

5.4.1. Do you care about mangroves?

When analysing the difference between the zones in whether they care about mangroves, resulting in n=138 for both years, see Figure 36 below for the distribution (10 rows in 2011 were deleted due to missing values). See Appendix L Figures 137 to 147 for the general statistics and statistical test outcomes.



a-A: *p=0.004, φ=0.22 (weak), χ^2 (1, N = 194) = 8.29
b-B: *p=0.001, φ=0.40 (strong), χ^2 (1, N = 82) = 11.6,
a-b: p>0.5, χ^2 (1, N = 138) = .38
A-B: p>0.1
t-T: *p=0.01, φ =0.22 (weak), χ^2 (1, N = 276) = 19.40

Figure 36 Percentual distribution of answers in 2011 and 2022 given to: Do you care about mangroves? in Ca Mau Province (yes/no) in the production (a & A) and protection (b & B) zone, and their summed responses (t & T). The chi-square test of independence was used on all sets of combinations, except for A-B, where Fisher's exact test was used. φ indicates the effect size when the results are significant.

The tests on Ca Mau level show that significantly fewer respondents answered to care about mangroves in 2022 than in 2011. This was also true for the production zone and the protection zone, where a strong effect was found for the latter. There is no difference in whether the respondents care about mangroves between the production or the protection zone. These results show that there has been a change in the perception of mangroves.

The following analysis aimed to determine whether there was a significant difference in whether farmers cared about mangroves in the production and protection zones in Nam Can in 2011 and 2022; see Figure 37 below for the distribution.

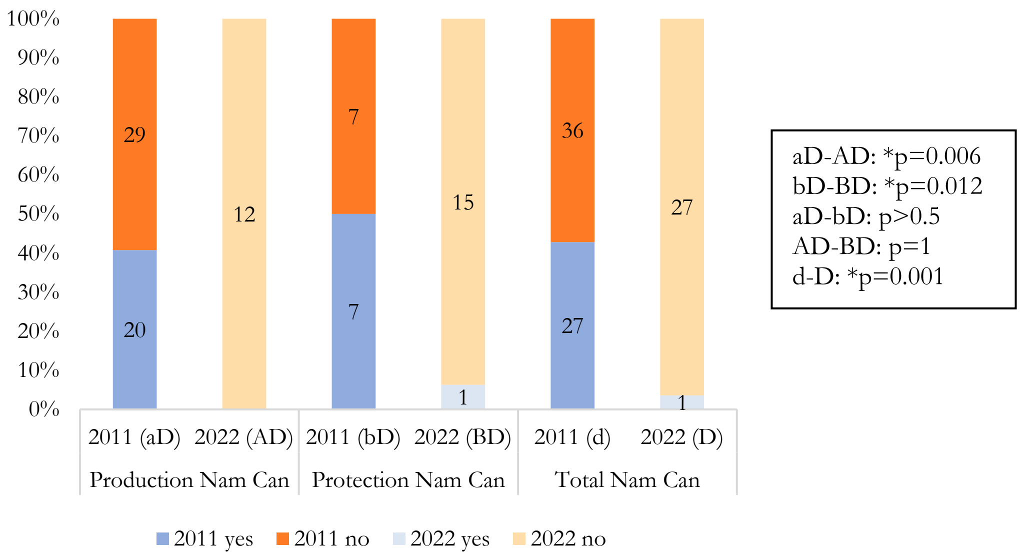


Figure 37 Percentual distribution of answers in 2011 and 2022 given to: Do you care about mangroves? in Nam Can District in the production (aD & AD) and protection zone (bD & BD), and their summed responses (d & D). Fisher's exact test was used on all sets of combinations.

These tests on Nam Can Level show that similar to Ca Mau level, significantly fewer respondents answered to care about mangroves in 2022 than in 2011, with no significant difference in the response given between the production and the protection zone. This shows that the implemented policies in consecutive years did not influence farmers' responses in Nam Can in a specific zone. However, did influence the general "caring" about mangroves.

5.4.2. Do you benefit most of forest exploitation, aquaculture, or both?

The following section analyses the responses of farmers in two separate mangrove forest management zones (production and protection) regarding what management they benefitted most from (forest exploitation, aquaculture, both, do not know), with 21 missing values deleted in 2011, resulting in n=127 in 2011 and n=138 in 2022; see Figure 38 below. See Appendix L Figures 148 to 158, for all general statistics and statistical tests outcomes. The tests on Ca Mau level show that significantly more respondents answered to benefit from aquaculture in 2022 than in 2011. This was also true for the production zone but not the protection zone. It is therefore claimed that fewer respondents in the production zone benefitted from forest exploitation with aquaculture in 2022 than in 2011.

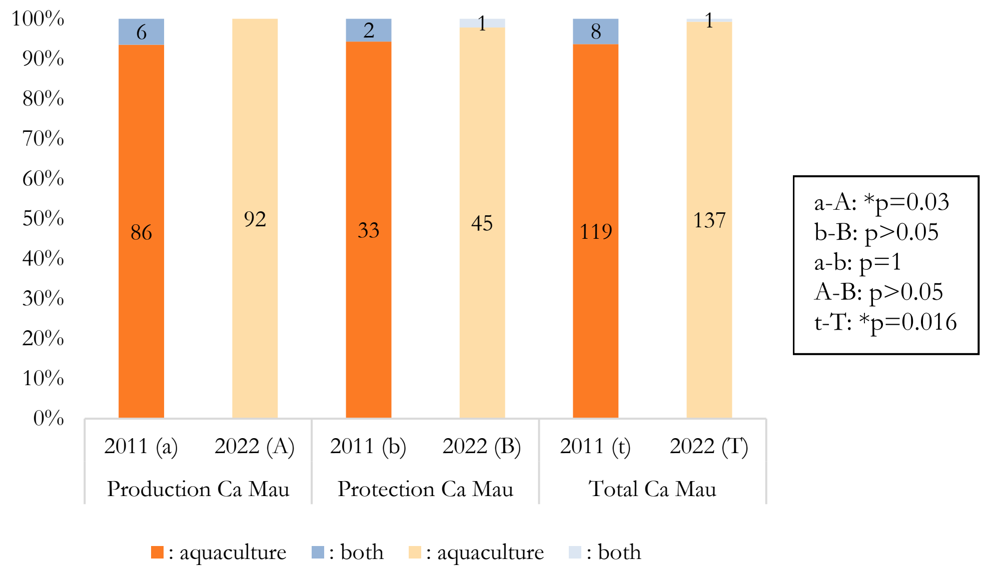


Figure 38 Percentual distribution of answers in 2011 and 2022 given to: What do you benefit most of? in Ca Mau Province (aquaculture or forest exploitation with aquaculture?) in the production (a & A) and protection (b & B) zone, and their summed responses (t & T). Fisher's exact test was used on all sets of combinations.

The following analysis aimed to investigate whether there was a significant difference in what farmers in the production and protection zones benefitted most from in Nam Can in 2011 and 2022; see Figure 39 below. The tests on Nam Can level show that there was no significant difference in what the respondents in Nam Can answered between 2011 and 2022 and between the zones. These results show no differences in financial benefits between the farmers in the different mangrove forest management zones in Nam Can.

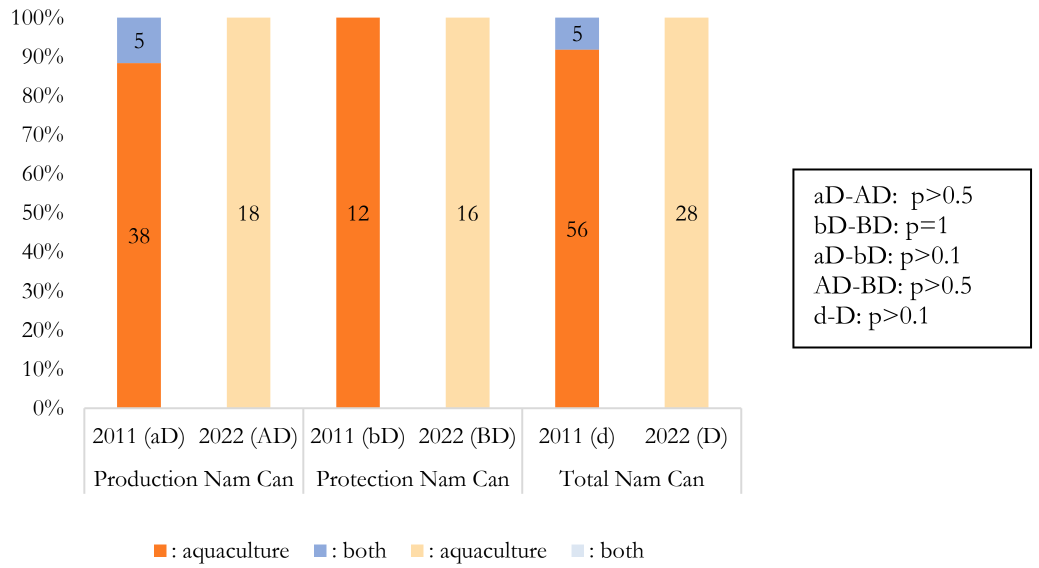


Figure 39 Distribution of answers in 2011 and 2022 given to: What do you benefit most of? in Nam Can District (aquaculture or forest exploitation with aquaculture (both)?) in the Production (aD & AD) and Protection Zone (bD & BD), and their summed responses (d & D). Fishers exact test was used on all sets of combinations.

5.4.3. Do you think this construction wood extraction in your land is allowed (legally)?

The following analysis examined whether there was a significant difference in opinions between the production and protection zones regarding the legality of construction wood extraction in Ca Mau in 2011 and 2022; see Figure 40 below. See Appendix L Figures 159 to 169, for all general statistics and statistical test outcomes.

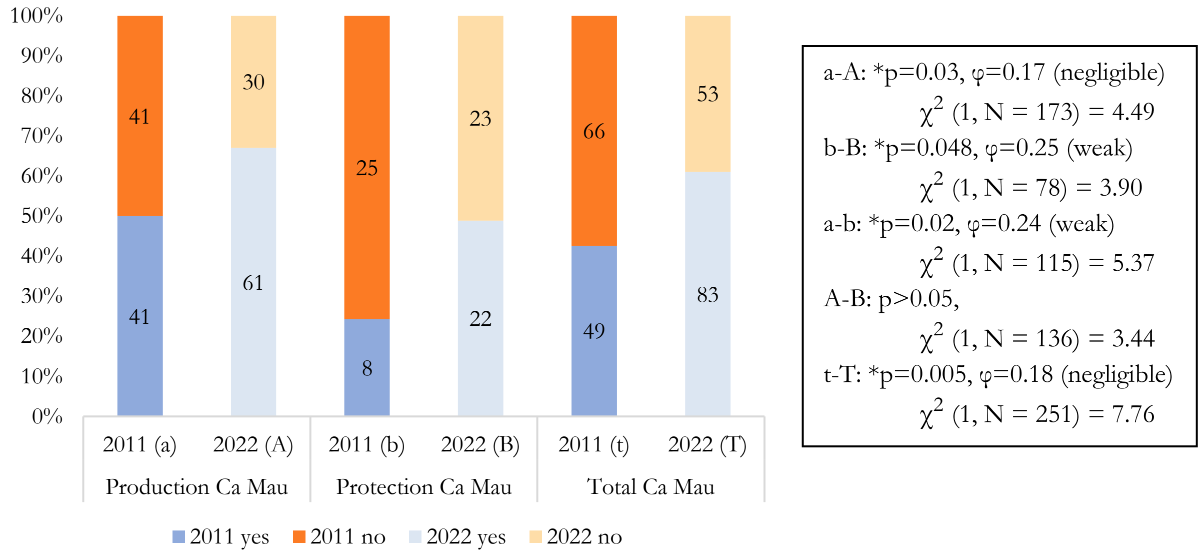


Figure 40 Distribution of answers in 2011 and 2022 given to: Do you think this construction wood extraction in your land is allowed (legally)? in Ca Mau Province (yes/no) in the production (a & A) and protection (b & B) zone, and their summed responses (t & T). The chi-square test of independence was used on all sets of combinations.

These tests on Ca Mau level show that, although the effect is weak, significantly more respondents answered that they thought construction wood extraction was legal in 2022 than in 2011. This also holds for respondents in the production (a-A) and protection zone specifically. In 2011, the responses differed significantly between the production and the protection zone, which was no longer the case in 2022. It is therefore claimed that significantly more respondents in the protection came to think that construction wood extraction was legal over time.

The following analysis aimed to investigate whether there was a significant difference in farmers' opinions in the production and protection zones regarding the legality of construction wood extraction in Nam Can in 2011 and 2022; see Figure 41 below. These tests on Nam Can level, show that respondents in both zones were more likely to answer 'yes' in 2022 than in 2011. Respondents in the protection zone answered 'no' significantly more than those in the production zone in 2011. In 2022 there was no significant difference between the zones. The results show that it was more clear to the respondents that construction wood extraction was illegal in 2011 in the protection zone. This changed compared to 2022. The results show that there is no perceived difference between the production and the protection zone anymore in 2022.

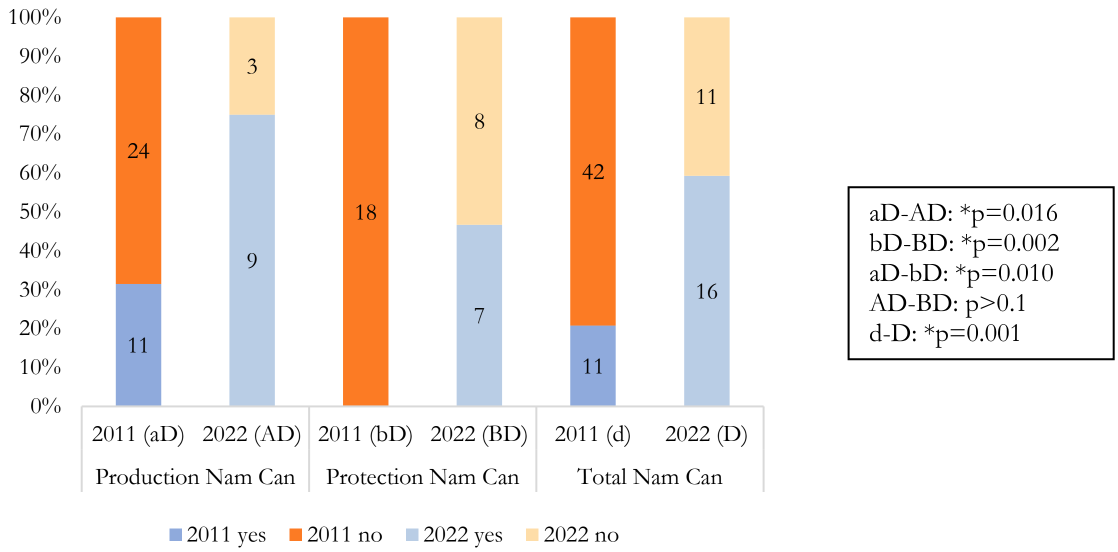


Figure 41 Distribution of answers in 2011 and 2022 given to: Do you think this construction wood extraction in your land is allowed (legally)? in Nam Can District (yes/no) in the production (aD & AD) and protection zone (bD & BD), and their summed responses (d & D). Fisher's exact test was used on all sets of combinations.

5.4.4. Do you think this fuelwood extraction in your land is allowed (legally)?

The following analysis examined whether there was a significant difference in opinions between the production and protection zones regarding the legality of fuel wood extraction in Ca Mau in 2011 and 2022; see Figure 42 below. See Appendix L Figures 170 to 180, for all general statistics and statistical test outcomes.

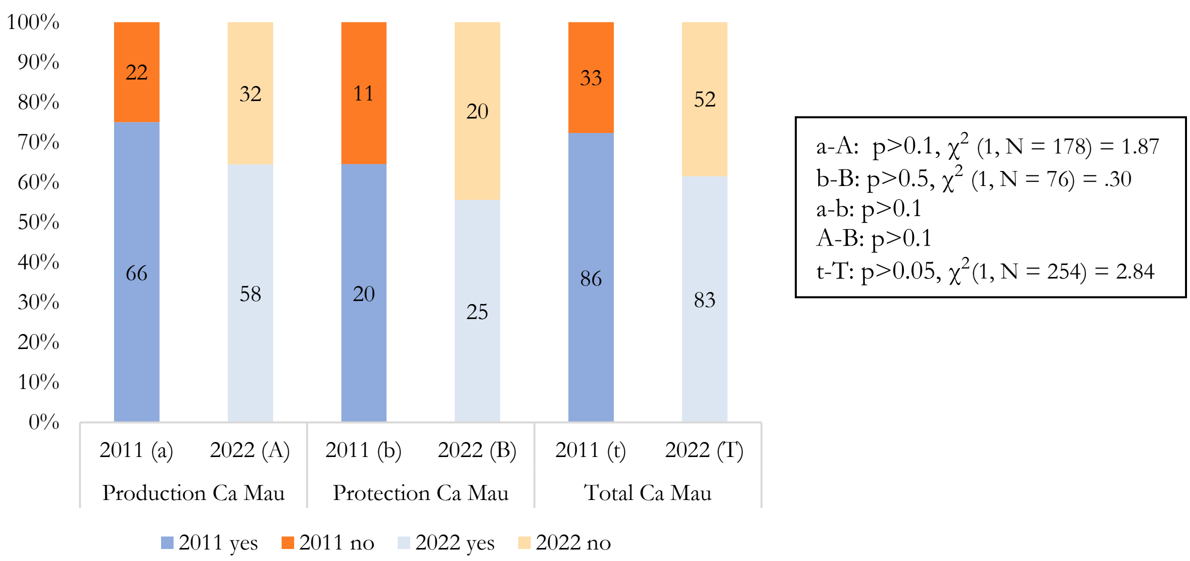


Figure 42 Distribution of answers in 2011 and 2022 given to: Do you think this fuel wood extraction in your land is allowed (legally)? in Ca Mau Province (yes/no) in the production (a & A) and protection (b & B) zone, and their summed responses (t & T). The chi-square test of independence was used on all tests, except for a-b and A-B, where Fisher's exact test was used.

These tests on the level of Ca Mau show no significant difference in the answer given in both years and zones, indicating that most respondents believed that fuel wood extraction was legal in both zones in both years in Ca Mau.

The following analysis examined whether there was a significant difference in opinions between the production and protection zones regarding the legality of fuel wood extraction in Nam Can in 2011 and 2022; see Figure 43 below. These tests on the level of Nam Can show that there was no significant difference in the answer given in both years and zones, showing that most respondents believed that fuel wood extraction was legal in both zones in both years in Nam Can.

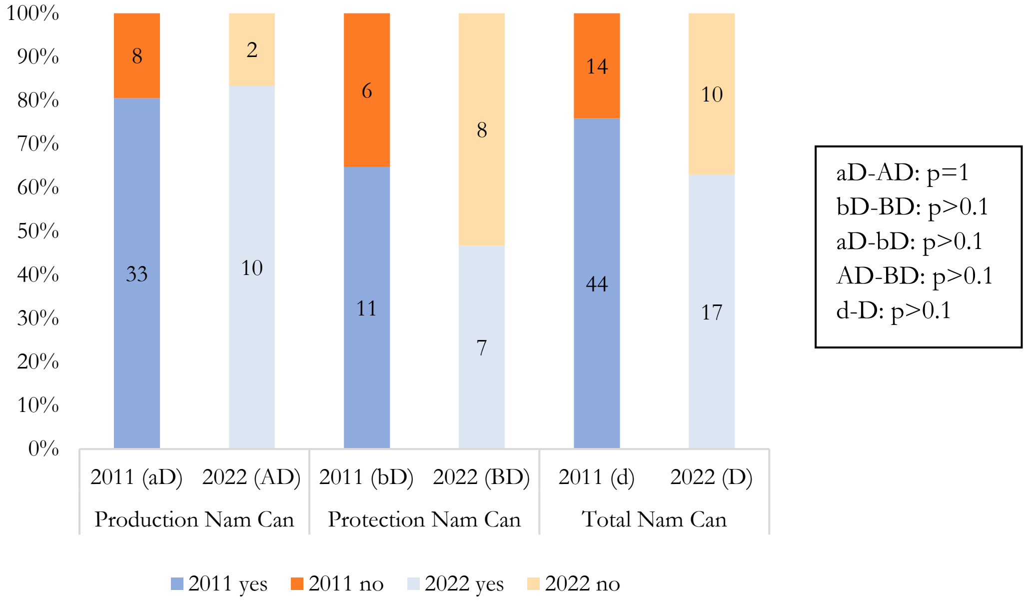


Figure 43 Distribution of answers in 2011 and 2022 given to: Do you think this fuel wood extraction in your land is allowed (legally)? in Nam Can District (yes/no) in the production (aD & AD) and protection Zone (bD & BD), and their summed responses (d & D). Fisher's exact test was used on all sets of combinations.

6. DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study represents one of the initial investigations into the efficacy of policy implementation in the forest management zones of Ca Mau. The following sections offer a discussion, limitations, and recommendations for future research pertaining to the research objectives. The Chapter is organized into the following sections: 6.1 The complicated implementation of policy instruments, 6.2 Remote sensing-based assessment of mangrove covers on-farm, 6.3 Understanding mangrove coverages using farmer's estimates, remote sensing-based estimates and policies and lastly, 6.4 Farmer perspectives and insights into mangrove management.

6.1. The complicated implementation of fragmented policy instruments

The following sections explore various aspects of the policy literature review. These sections cover topics such as the interpretation of forest policies, the conflict between long-term and short-term goals within policies, the intricate nature of land and forest ownership, the significance of trust and local involvement in policy implementation, the importance of up-to-date land unit delineation for accurate assessment of land use rights and ownership and the effects of the accessibility to farms on forest management and monitoring. Each section provides valuable insights into the complexities and considerations involved in understanding and effectively implementing forest policies.

6.1.1. Interpretation of forest policies

Most legal documents were available only in Vietnamese, and their translation might have caused confusion. For example, some literature used the terms ‘production forest’ and ‘production zone’ interchangeably. This is a prime example of how the language barrier might have caused misunderstanding. In this research, the protection forest is assumed to be present in the protection zone, and the production forest is in the production zone. Future research is recommended to work with a translator to avoid these occurrences as much as possible. Terminologies used to describe mangrove coverage on-farms versus mangrove-to-pond ratios imply different levels of mangrove presence. Therefore, it is important to streamline the variables used to facilitate better understanding and consistency in monitoring efforts in the future.

Interviews during the field trip with forest managers demonstrated that mangrove forest legislations are fragmented and challenging to understand and follow for farmers (Personal communication, April, 2022). This aligns with the research objective’s (1) results, which show that mangrove forest management is overlapping and complex to interpret for farmers. Multiple institutions carry out forest monitoring, utilizing varying variables and scales. Data sharing contradicts results between institutions (General Department of Land Administration and the Forest Protection Department) and ultimately do not provide an accurate status assessment of the mangrove in Vietnam. Data sharing between local forest rangers, surveys, and remote sensing platforms remains uncertain. However, the FORMIS platform might form a viable solution to this problem.

Additional continuous enactments and (partial) repeals of legal instruments add to the confusion of obligations regarding the mangrove coverage on-farm. Sometimes Laws are repealed or amended, and a new Law is implemented and gets enacted with co-existing directives or Decrees to aid their implementation. New Laws may refer to directives and Decrees that have not been updated and that still refer to the old

Laws (which have been repealed). To obtain eco-certification, farms must meet a minimum coverage of mangrove on-farm and other specific management practices (i.e. the Naturland certification requiring 50%). This eco-certification percentage is lower than the 60% threshold specified for the protection and production zone. This means that farmers with eco-certification in the production zone are unable to cut down 100% of the mangroves for thinning purposes (as per Decision 178), as it would not comply with the eco-certification requirements.

As shown in Table 11, many obligations for farmers remain unclear, as indicated by "?". These question marks are partly present due to a lack of information, as well as not being able to read Vietnamese. However, aside from the language barrier, which possibly caused a lessened understanding of the policies, other research confirms a lack of clarity in policy documents regarding the obligations of mangrove cover on-farm for shrimp farmers.

6.1.2. Policy clash between long-term and short-term goals

Policies are implemented to conserve and restore the mangrove ecosystems. However, as the focus is mostly on production whilst implementing a certain amount of mangroves, the focus is side-tracked and not on mangrove ecosystems anymore. This is such a delicate and wicked system that specific measures are required to succeed. In the production zone, mangroves are harvested mostly for charcoal, which is unsustainable and may damage ecosystems when harvested in a too-short rotation cycle. Therefore, policies promoting long-term sustainable energy solutions are needed to restore mangrove degradation and support their recovery.

There is a need to balance short-term economic goals with long-term ecological sustainability. The current national policy prioritizes high productivity, leading to increased aquacultural intensification. This research results align with previous research, which investigated the mangrove-to-pond ratio for sustainable shrimp farming in mangrove-shrimp practices in Vietnam (Baumgartner et al., 2016). This research showed that short-term goals and economic motives are the main drivers for farmers to implement lower mangrove-to-pond ratios. This is confirmed by other research, like Costanza (et al.) of 1997, who stated that short-term economic goals could lead to undervaluing ecosystem services and result in undefined property rights, creating a significant challenge for the protection of biological resources.

Vietnamese government policies encouraged development and aquaculture in mangrove areas for short-term economic gains (Hawkins et al., 2010). Chapter 2 further demonstrates a decline in the proportion of mandated mangrove coverage on farms, despite the Vietnamese Government's assertions of "restoring" mangroves through its policies (refer to Decisions 57/1985/QD.UB, 389/1988/QD.UB, 24/2002/QD-UB, and 19/2010/QD-UBND). To achieve a development, or increase, of aquacultural production, farmers take short-term informal loans with high-interest rates, prioritizing quantity over quality to repay the loans. This approach increases disease risk and unsustainable practices (Joffre et al., 2018a). Shrimp yield failure weighs most on small shrimp farms and poorer households. Stocking underqualified fry (shrimp or crab) and little pond preparation makes shrimp die young (Ha et al., 2013). Combining the framework of productivity targets and credit access for small-scale farmers could promote sustainable aquacultural practices in the Mekong Delta. This approach would focus on pond ecology, increase farmers' knowledge and awareness, and create disease-resilient ponds (Joffre et al., 2018a).

6.1.3. Complex land and forest ownership

The current jurisdictional system in Vietnam is set up so that many different parties are involved in mangrove cover management. Overlap between the different parties involved causes complexity and a lack of clarity for the farmers. In Vietnam, the ownership regime for forests can result in landholders having greater rights to the land they are allocated than the forests on that land, as per the Law on Forest Protection and Development[78] (Hawkins et al., 2010). This results in overlapping forest ownership between the MARD and MONRE, which complicates mangrove management and eventually results in the continuation of mangrove deforestation[79]. This also shows in the current monitoring system for mangroves on-farm, which consists of multiple institutions from the land use, forest monitoring, and planning departments performing overlapping work. However, although overlapping, this work seems to be lacking in enforcement in the field, as illegal logging remains a problem. Informal interviews in the study reveal that much of the management of integrated mangrove-shrimp farms is unmonitored (personal communication, anonymous farmer, April, 2022). Farmers can manage their farms and mangroves as they desire. It is remarkable how Commune People's committees seem primarily responsible for forest monitoring, even though the forestry service probably would have more real expertise. Education of Commune People's committee members on the importance of mangrove monitoring could aid this problem.

Various countries have attempted mangrove restoration, like South Sulawesi in Indonesia, where the uncertainty of *de jure* access caused ambiguity regarding the property status of mangrove forests, leading to the formulation of multiple layers of property for various products, services, and benefits (Wylie et al., 2016). This made the area vulnerable to conversion into settlements, ponds, and other uses, threatening the mangrove forest's long-term existence. This is similar to Vietnam's situation and shows the effects of overlapping tenure rights on successful mangrove restoration. Legal access to the community to manage mangrove forests could aid in solving this problem by decreasing the number of stakeholders involved (through forest management boards and forest companies) (Suharti et al., 2021).

This shows that Vietnam is not the only country struggling with its jurisdictional system and complex land and forest ownership and access rights. Continuous unclarity is not benefitting the conservation and restoration of mangroves. Ha et al. (2012) have shown that people are more likely to participate in forest activities when they have more benefits (thus access) from forests. Therefore, this is a crucial factor in successful mangrove restoration. Research suggests that changing governance structures, social norms, and cultural values is crucial for successful mangrove restoration and aquacultural productivity (Bush & Marschke, 2014). The Vietnamese Government seems to be aware of the currently complex jurisdictional system. It implemented a Decision back in 2014 (1976/QD-TTg80) on assessing, identifying identical, overlapping issues, and working out a roadmap for revision and proposal of legal documents to ensure uniformity and effectiveness. This indicates progress, as an appropriate forest management plan is necessary for the sustainable harvesting of mangroves and utilising natural forests (Luong, 2014).

This research, therefore, suggests that simplifying the jurisdictional system could lead to a better understanding and implementation of policies. Future research is recommended to assess overlaps between institutions and departments regarding mangrove cover management to determine superfluous ones. Finally, possibilities for mitigating these should be determined, and opportunities for increased benefits for farmers should be identified.

[78] Luật bảo vệ và phát triển rừng [Law on forest protection and development], No. 25/L-CTN (Dec. 14, 2004)

[79] Asides from land monitoring, and forest planning overlaps, mangroves on mangrove-shrimp farms a part a much larger network of legality. Such as the departments of agriculture and fisheries, water management, food safety and import, and trade and export (nationally and internationally).

[80] Quyết định phê duyệt quy hoạch hệ thống rừng đặc dụng cả nước đến năm 2020, tầm nhìn đến năm 2030 [Decision on approving the master plan on the national special-use forest system through 2020, with a vision toward 2030] No. 1976/QD-TTg (Oct. 30, 2014)

6.1.4. Establishing trust and local involvement for successful policy implementation

A lack of trust has been a key identified issue between local communities and forest departments due to previous negative experiences or perceptions of unfair treatment and a lack of transparency and communication (Ha, 2012b; Ha et al., 2014; Jhaveri et al., 2018). Trust is established through middlemen, who establish and maintain stable network relationships with farmers, wholesalers, and input suppliers (Nguyen et al., 2021a). However, these middlemen cause implications, as further described in Section 6.1.6.

Trust between local communities and forest departments can be increased through local involvement, where the dependency on middlemen might become redundant. People's committees can play a key role in building trust between local communities and forest departments by acting as communication bridges and promoting transparency and accountability in the management of forest resources. They empower local communities and ensure that their needs and concerns are heard and addressed. Recent studies demonstrate that the involvement of local communities and indigenous knowledge can aid successful mangrove restoration. Such as the community-led initiative "Mikoko Pamoja" in Kenya in 2010, which involved residents in planting mangrove seedlings (Siago, 2021). This reforestation program operates on payments for forest ecosystem services. The project's impetus increased when local villagers realized that the mangrove forest was not a government-owned property and that relying on external intervention was not feasible. This realization sparked the need for community participation in mangrove conservation and the pursuit of natural solutions to improve livelihoods (Spalding & Lael, 2021). The project's success can be attributed to its small-scale approach, which facilitated local engagement and simplified operations, minimizing the additional costs and administrative complexities associated with complying with intricate global mechanisms. Nevertheless, many developing countries face challenges in channelling funding through the government, further complicating conservation efforts (Wylie et al., 2016). This aligns with other research that states that participatory approaches involving local communities and stakeholders in decision-making aid sustainable aquacultural transitions (Bush & Marschke, 2014).

6.1.5. Up-to-date land unit delineation for land use rights and ownership

This research assumes that the shrimp farming boundaries remained the same between 2011 and 2019. However, these boundaries are not static and are subject to change over time. Assuming that they remain constant may lead to inaccurate representations of the study area. Farmers are allowed to lease more land and expand their farms, while new areas of forests are added as production and protection forests each year. Therefore, access to up-to-date data and boundaries is crucial for future research. Mangrove and land use monitoring institutions could benefit from an integrated platform like FORMIS, which provides open access to boundary data for scholars and the general public. This open access to data could contribute to the successful restoration of mangroves through more accurate and up-to-date research.

Research performed by Morales et al. (2021) proposes a fit-for-purpose concept which consists of a community-involved solution for collecting land registration data using a cell phone app and external GPS receivers. The solution includes collecting polygons to represent land units, validating data with neighbours, and recording information in official government systems. The proposed solution captures various people-to-land relationships whilst meeting predefined methodological requirements and provides a comprehensive overview of land rights that empowers the government to protect citizen rights. The system uses a multi-level data model compliant with the Land Administration Domain Model standard and corresponding country profile (Morales et al., 2021). A similar method could possibly be a solution for Vietnam to update their databases in an affordable and scalable manner.

6.1.6. Poor accessibility to farms hampers forest management and monitoring

Both policy zones are located in a remote region of Vietnam, where the accessibility to farms is poor. This remoteness probably hampers successful monitoring and implementation of intended forest management. Poor accessibility is caused by interconnected waterways of canals, ditches, and poor soil conditions (Stoop et al., 2015). Relative worse accessibility causes integrated mangrove-shrimp farms to have a lower income due to poor infrastructure and long travel distances to markets (Ha et al., 2013). Poor infrastructure causes farmers or producers to be dependent on middlemen to connect them to buyers. These middlemen ensure that the shrimp are bought from them at a set price and sold to exporters or processors, but bargaining with buyers is possible (Nguyen et al., 2021a).

Based on fieldwork experiences, this study provides evidence that inadequate infrastructure access can impede the analysis of mangrove ecosystems on farms, which, in turn, can hinder effective monitoring and management. The lack of access roads and bridges makes detecting and addressing issues like illegal logging and poaching challenging. Furthermore, limited infrastructure can also restrict the participation of local communities in restoration activities and ecotourism, resulting in a decrease in the economic and social advantages of mangrove rehabilitation. Therefore investment in infrastructure is the highest priority for the government because a good infrastructure increases farmers' livelihood options and improves their access to education and technology, eventually creating better, more resilient mangrove ecosystems (Ha et al., 2013).

Recently, the poor infrastructure in Ca Mau, and its effects on mangrove management became an increasingly hot topic (Dang, 2022; Peoples Committee, 2019; Trinh et al., 2020). Asides from infrastructural development, future research could use the previous sections on the usage of UAVs (such as research by Pasaribu et al. 2021) and local involvement to help mitigate the negative effects of poor infrastructure on mangrove management and support the restoration and conservation of these critical ecosystems.

6.2. Remote sensing-based assessment of mangrove covers on-farm

The following sections delve into various facets concerning remote sensing-based mangrove classification. These sections address the availability of data, the applied method, challenges related to multi-sensor classification, the effects of water levels, and patterns observed in mangroves and propagule covers. Each section provides valuable insights into the complexities and considerations involved in accurately classifying mangrove ecosystems using remote sensing techniques.

6.2.1. Data availability in tropical and cloudy Vietnam

Remote sensing is emerging as a valuable tool for monitoring and assessing changes in mangrove coverage. However, cloud cover and other environmental factors influence the availability and quality of remotely sensed data, impacting subsequent analyses' accuracy. Vietnam is located in a tropical area with regular cloud cover. Cloud cover affects the amount (see Appendix M Figures 181 and 182 for the ordered study area at the European Space Agency) and quality of solar radiation reaching the Earth's surface. This, in turn, impacts the spectral reflectance of different land cover types, including mangroves. The unique spectral signature of mangroves is obscured by cloud cover, leading to inaccurate classification and mapping. Furthermore, cloud cover impacts the temporal resolution of remotely sensed data, which leads to missing data in time series. This missing data introduces biases in the analysis and affects the accuracy of the resulting trends. It is essential to consider these factors and their effects when designing remote sensing studies to ensure that the resulting data is suitable for the intended analysis.

This is also the case in this research, where due to the time gap of more than 8.5 years between the two images, this research is limited to performing change detection instead of mangrove forest monitoring, which requires time series analysis of sufficiently high frequency. Using drones (or Unmanned Aerial Vehicles -UAVs) mitigates the impact of cloud cover on mangrove cover analysis. Vietnam would benefit greatly from implementing drones, as this would provide greater flexibility in data acquisition timing, with the added benefit of being able to fly under cloud cover. This helps capture detailed information on mangrove forest structure and density obscured by cloud cover in satellite imagery. However, the Government should enable and facilitate flying drones for forest inventories. Currently, this is hardly possible, clearly hampering the development of up-to-date and good-quality forest maps. To enhance the success of mangrove restoration efforts, future research must be conducted to explore effective techniques for mitigating cloud cover during mapping[81]. Therefore, it is recommended that further research aims to identify and evaluate such techniques to enhance the accuracy and reliability of mangrove mapping and ultimately contribute to the successful restoration of mangrove ecosystems. Future research is recommended to explore deep learning techniques to mitigate the problem of cloud cover in mangrove mapping, such as research by Lomeo & Singh (2022). The research suggests a cost-effective framework that uses cloud-based earth observation data and deep learning to monitor and map mangrove forests. This empowers local communities to generate new training data, monitor changes, and identify illegal deforestation activities. It can aid in cost-effective, successful mangrove restoration. This method is beneficial for successful mangrove restoration in South Vietnam, where cloud cover can hinder traditional monitoring methods (Lomeo & Singh, 2022).

6.2.2. Segmentation and classification methods

As described in the methods, image segmentation was intended to be performed using digital segmentation techniques in eCognition. Image objects were created using multi-resolution segmentation on the 2019 GeoEye imagery, as the higher resolution could aid the segmentation process. For the image analysis of the satellite images, several algorithms of multiresolution segmentation techniques for high-resolution imagery on pixel level were tested for mangrove cover mapping. Various combinations of parameter settings (scale, colour/shape, smoothness, and compactness) ran on a subset in multiresolution segmentation.

Multiresolution segmentation settings were based on previous research (Cardenas et al., 2022; Clinton et al., 2008; Kavzoglu & Tonbul, 2017; Khadanga, 2014). Image layer weights were altered to find an optimum segmentation for the image. Subsequent information extraction of image objects (polygons) aided the classification of the objects. The classification was done using similar characteristics within a group. Mangrove forests can usually be well segmented from a simple visual interpretation of spectral values of the colour composite, using parameters like colour, texture and structure (Van et al., 2015). Removal of non-mangrove classes was performed by classifying them into preliminary classes based on spectral values. Many spectral values were tested, like brightness, Stddev, ratio to neighbours, shape, mean of red, green and blue and NIR values, Normalized Difference Vegetation Index (Yang et al., 2019), Normalized Difference Water Index (Muhsoni et al., 2018), etc., as well as geometrical values like shape index, and textural (contrast) as described by (Cardenas et al., 2022). Eventually, brightness (reflectance value) was a good criterion for classifying non-vegetation (Béland et al., 2006; Tong et al., 2004b). See Table 19 below for Preliminary Class Codes (PCC) based on Spectral Values.

[81] This might also include developing better haze and cloud removal technologies.

Table 19 Preliminary class codes as used for Digital Segmentation in eCognition

Preliminary Class Code (PCC) based on spectral values	Visual Characteristics
1	Dark green course texture (in a pond)
2	Mixed/light green course texture (in a pond)
3	Dark green fine texture (in and outside a pond)
4	Green fine texture (in and outside a pond)
5	Smooth, brownish green to very light brownish green
6	White and smooth
7	Red/purple, coarse texture
8	Black or nearly black

Usage of different indices to distinguish vegetation from non-vegetation, like the Normalized Difference Vegetation Index for non-vegetation (PCC 6, 7) and the Normalized Difference Water Index specifically for waterbodies (PCC 5) (Muhsoni et al., 2018). Shadow was removed by using the Brightness values (PCC 8). Trees were separated from other vegetation (e.g. grass) using texture and the Canny Edge Filter (Chouhan & Shukla 2011; Mudau & Mhangara, 2019) and the Tree Grass Difference Index (PCC4) (Qian et al., 2020). On visual inspection, this showed to be performing well. Consequently, mangrove trees were attempted to be separated from other trees using a ratio of the spectral reflectance distance between NIR to red and green to red ([NIR-red]/[green-red])(PCC 3) (Kamal et al., 2015). This last step was difficult, as individual mangrove trees were standalone and had few distinct features from other trees. Consequently, the whole ruleset was run on the entire study area, the non-mangrove classes were filtered out (PCC3-8), and the remaining objects (PCC 1 and 2) were exported to GIS. Overlaying the random sample manual delineated polygons with the digitized polygons showed too little accuracy (<80%) as assessed by using goodness over fit (D), based on (Clinton et al., 2010). Where area($x_i \cap y_j$) is the area of the geographic intersection of the (manual) training object x_i and digital segment y_j.

$$\text{Over Segmentation} = 1 - \frac{\text{area}(x_i \cap y_j)}{\text{area}(x_i)}, \text{ Under Segmentation} = 1 - \frac{\text{area}(x_i \cap y_j)}{\text{area}(y_j)}, D = \sqrt{\frac{\text{Over segmentation}^2 + \text{Under segmentation}^2}{2}}$$

Small shadows between individual mangrove trees cause low accuracy. These small patches of shadows are dark green and sometimes much like dark patches of mangrove trees, causing an occasional discrepancy between the shadow and the mangrove. Shadow potentially is classified as (a dark patch of) mangrove. The usage mentioned above of multiresolution segmentation and object-based image analysis were promising methods in the eCognition software (Hossain & Chen, 2017). However, they did not provide significant results in this research. It was chosen to manually segment both images, as this would provide more accurate estimations of mangrove cover on-farm. Research by Hossain and Chen (2017) showed that recent developments in the collaboration of segmentation and classification methods, like in eCognition, have shown that segmentation does not have to be perfect. However, classification can overcome these inaccuracies when there is a case of over-segmentation and not under-segmentation, which was not the case in the method attempted above.

The manual sampling method used in the study was labour-intensive and time-consuming, resulting in limited sample size and fragmented data. Nonetheless, it did lead to high segmentation accuracy and reliable results. To improve the study's representation and reduce limitations, it is suggested to increase manual sampling, select additional satellite images, expand the study area, or use digital image processing techniques. However, it is important to note that the study's findings should be considered indicative of the trends in mangrove management. The algorithm used to translate the image characteristics into field classes for monitoring should be tested to apply the algorithm to other areas outside of this particular study area. Additional validation over time will also be necessary.

6.2.3. Multi-sensor classification difficulties

The availability of alternative high-resolution satellite data in the study area is limited, and considering cloud-free data, the options become limited. Therefore data from two sensors was chosen and used for the image analysis. These different sensors add complexity to change analysis. These complexities were considered and mitigated to the extent possible. Classifications between images differ as coarser resolution detect fewer elements than finer resolution images. The GeoEye image has a finer resolution (0.4m) than the Quickbird image (0.5m). This would cause a discrepancy between the images as a finer resolution can detect elements better than a coarser image, in which these might not appear (Mondino & Chiabrando, 2010; Serra et al., 2003).

Spectral information and sensitivity of the GeoEye and Quickbird sensors differ (Serra et al., 2003). See Table 8 for the spectral information. Since the sensor sensitivity and the wavelengths differ between the GeoEye and the Quickbird Imagery, the difference between pixel values in the RGB spectrum can vary within one image but also between images. Therefore, one "lighter" tree in one image might remain undetected in another image. Different coloured patches can indicate either different mangrove species or different ages of trees. This spectral information is, in turn, also influenced by the time of capture. The spectral response of many cover types varies throughout the year: categories that appear very similar in spring may become distinguishable at earlier or later stages of the annual cycle (Serra et al., 2003).

The mangrove segmentation was initially subdivided between dark, mixed, and light mangrove-classified polygons. However, as these distinctions were fuzzy due to the differing spectral values of both imageries, it was chosen not to distinguish between them. The problem of shadows was lessened in the manual delineation, as it was visible when there was dark mangrove with a lower crown height or whether it was a shadow. This manual classification of propagule and mangrove was visually based, limiting replicability, but this method does provide higher segmentation accuracy. Distinguishing propagules from mangroves was found to be challenging, as mangrove trees are considered as "coverage" only when they reach a height of 1m, which was estimated using shadow pixels in this study (see Appendix N Figure 183). Pixels less than 1m were classified and delineated as propagules, but due to the different pixel sizes between the images, the distinction between the mangrove and propagule classes was fuzzy. The accuracy was attempted to be maintained by consistently zooming in to around 1:350 in both images, but the Quickbird image is likely to be classified less accurately than the GeoEye image due to the difference in pixel sizes. This may have impacted the estimation of propagule polygons and the research objectives related to the distribution and abundance of mangrove propagules. The fuzzy distinction between the mangrove and propagule classes could have led to overestimation or underestimation of mangrove propagules, potentially leading to erroneous conclusions. As described in Methods Chapter 4, this research allows to classify mangrove trees at least 1.9 meters tall in the 2011 image and 2.1 meters tall in the 2022 image, almost double the required height. It is therefore important to acknowledge that some of the propagule classified polygons should be classified as mangroves.

Accurate classification of mangrove forests is essential for effective forest management, as it provides information on their extent and distribution. Incorrect classification due to slightly misfitting imagery can result in the mismanagement of mangrove forests, leading to inappropriate land use Decisions or neglect of important mangrove areas. The manual delineation allowed the classification of mangrove trees of at least 1.9 meters tall in the 2011 image and 2.1 meters tall in the 2022 image, almost double the required height. This means polygons classified as propagules are probably partly also mangrove trees of 1 metre and above, as the threshold to distinguish between propagules and mangroves was 1 metre. This had led to an underestimation of mangrove cover on-farm, and an overestimation of propagules on-farm.

6.2.4. Water level effects on remote sensing-based classifications

The accuracy of image segmentation and classification is affected by the Quickbird and GeoEyedata acquisition dates, weather conditions and water level. The tides in Ca Mau have an amplitude of one to two meters (Tong et al., 2004). The uncertainty of whether farmers open ponds' sluice gates further impacts water levels on-farm. High or low water levels significantly affect manual segmentation, as high tide and surface-level water can cause the misclassification of submerged propagules. In addition, mangrove crowns' height and minimum height requirement of one meter cannot be accurately estimated if they are lower than the surrounding mangroves.

Based on historical tidal measurements and lunar observations, the Quickbird image was captured after low tide, and the GeoEye image was captured after high tide, neither on a new nor full moon day[82] (Bảng thủy triều,2023). Since both images were not taken during spring tide, they do not provide significant information on whether the farmers opened their sluices to inlet new water or drain their ponds. It is possible that there were lower water levels in the Quickbird (2011) image due to water being released by opening the sluice gates during low tide. Higher water levels in the GeoEye (2019) image may have occurred due to new water entering the ponds as a result of opening the sluice gates during high tide, which could have resulted in under-segmentation in the 2019 imagery. However, as described in the introduction, the opening and closing of sluice gates vary depending on the shrimp farmer's preferences. Future research may further investigate the possibility of using the mangrove crown diameter as an indicator of tree height, using approaches like Galvincio & Popescu (2016) and Suhardiman et al. (2016). This can be used to simplify the identification of mangrove trees without considering the tidal levels and identify trees that meet the minimum height requirement of one meter.

6.2.5. Mangrove and propagule cover patterns in the different forest management zones

The results of manual delineation are in line with other research by Thuy et al. (2022) that states that most mangrove-shrimp farms have yet to achieve the compulsory tree cover percentages required by the regulation. Propagule covers did not differ between the mangrove forest management zones or over time, even though it would be expected that farmers in the production zone have more propagules due to more flexibility regarding their mangrove logging on-farm (according to National Decision 178), suggesting the lack of differentiation between the mangrove forest management zones. This research shows that around half of the propagules delineated in 2011 transformed into mangroves in 2019, and a large number of mangroves became other, which means either it has been cut down or the layers were not precisely on top of each other, resulting in inaccurate classification. Research by Thuy et al. (2022) showed that, in general, there was an increase in mangrove cover in Ca Mau between 2016 and 2020. Even though the results of this

[82] New moon on 3rd of February and full moon on 18th of February 2011. Full moon on 12th of December and new moon on 26th of December 2019.

research can't be used for forest monitoring, the results of the change detection do align with a slight increase found in other research.

6.3. Understanding mangrove coverages using farmer's estimates, remote sensing-based estimates and policies

The following sections delve into various aspects, including the influence of surveyors on farmers' responses and subjective influences, the significant overestimations made by farmers regarding their mangrove cover on-farm, the effects of shrimp farm areas on mangrove management, and the importance of proximity to open water.

6.3.1. The influence of surveyors on-farmer responses and subjectivity influences

In the survey analysis, a comparison was made between responses from Nam Can and Ca Mau in different mangrove forest management zones from 2011 to 2022. Farmers were asked to estimate their mangrove cover on-farm in the surveys of 2011 and 2022. As explained before, depending on the authority of the surveyor, farmers might overestimate these cover percentages to avoid trouble. The question regarding whether respondents care about mangroves is primarily intended to provide context, as the definition and measurement of "care" are subjective and vary from person to person. Therefore, it is a challenging metric to quantify. Similarly, the question about whether respondents benefit more from aquaculture, wood exploitation, or both can create uncertainty about the meaning of "benefit." It is unclear whether the question is referring to economic or social benefits. However, it is assumed to refer to the former. Additionally, the surveyor may influence the questions on the legality of logging for construction or fuel, as the respondent's awareness of authority could impact their answer. Future surveying can mitigate these issues by ensuring that all surveyors follow a standardized protocol for administering the survey to eliminate the potential for biased questioning or interpretation. Anonymous surveying might also reduce the potential for respondents to feel pressure to provide socially desirable responses or to be influenced by the surveyor. Future research is recommended to look into survey methods that allow anonymous answers (e.g. workshops with local farmers, polls via mobile phones), as these may provide great opportunities to collect additional info.

6.3.2. Farmers' significant overestimations of mangrove cover on-farm

The results of the analysis of farmers' estimation of mangrove cover on-farm in Ca Mau show that in 2011 and 2022, there was a significant difference between the estimates of farmers in the production and protection zone. Farmers in the protection zone estimated their mangrove cover on-farm higher than in the production zone. This could indicate that farmers in the protection zone believe their mangrove cover on-farm is/should be higher than those in the production zone. Whether they truly have a higher cover of mangrove on-farm is not known. It is important to note that farmers can log at any time in the production forest and protection forest as long as they comply with the rules and regulations: farmers can log mangroves with a volume of ten m^3 anytime per unit area per three years (as per Decision 178). This means mangroves could be there one day whilst it is gone the next day. Looking at biomass estimations (Muhsoni et al., 2018), ten m^3 of mangroves equals around 92 m^2 of mangroves[83]. However, assuming a production cycle of 15 years, the chance that this happened is improbable. Therefore, asking the farmers to estimate their mangrove cover may refer to how much they have on average, not at a specific moment (such as by manual delineation).

[83] (10 m^3) x (1000 L/m^3) x (0.97 $ton/100\ m^2$)/ (1.0 ton/metric ton) = 97 m^2

In this research, the estimated mangrove cover percentages by farmers in Nam Can are around 50%, which is in line with research performed by Tran et al. (2021), which used farmers' estimations of their mangrove-to-pond cover ratios in Tam Giang Commune within Nam Can District, Ca Mau Province. The results showed a range of mangrove cover percentage estimations of farmers from 42.00% to 72.50%[84] (note the interchangeable use of ratio and mangrove cover %) (Tran et al., 2021).

This research indicates a significant overestimation of mangrove cover on-farms in Nam Can in 2011, in both the production and protection zone, compared to the remote sensing-based estimates. This suggests that the surveyor may have a real influence on the farmers' estimates or that the farmers are aware that they are not complying with the regulation of having 60% of mangrove coverage on-farm. This overestimation might be due to the misuse of the terminology, as described in the Introduction. Policies refer to mangrove coverage on-farm, but if farmers assume this refers to the mangrove-to-pond ratio, they would have to implement fewer mangroves to fulfil the 60:40 ratio than to comply with the 60% mangrove coverage on-farm. If farmers are asked about ratio or mangrove coverage (used incoherently), overestimation is more likely. Remote sensing-based estimates (with accuracy assessment) can more accurately determine the mangrove cover on-farm than farmers' estimates. Higher accuracy would create a better understanding of the current state of mangroves (on-farm) is created. This can help create an accurate image of the current mangrove restoration and conservation state.

6.3.3. Shrimp farm area effects on mangrove management

As mentioned earlier, larger shrimp farms have the advantage of having more resources and capabilities to establish greater mangrove cover. However, they also encounter challenges associated with the scale of their operations, such as managing higher production volumes, dealing with complex logistics, and meeting more extensive regulatory requirements. The results show no significant correlation between shrimp farm area and mangrove cover percentage but did show a significant correlation between shrimp farm and area of mangrove on-farm. However, despite this correlation, the mangrove estimates are still under the required coverage they should be. The results show no correlation between mangrove % on-farm and shrimp farm area, confirming that Decision 24/QD-UB is either ineffective or no longer visibly influencing mangrove cover management on farms. This is expected as this Decision is repealed by Decision 19/QD-UBND[85] of 2010.

6.3.4. The importance of distance to open water

The buffer zone exhibited a significantly higher estimation of mangrove cover compared to the economic zone. However, no notable distinction was observed between the full protection zone and the other zones, potentially due to limited sampling within the full protection zone (n=4 in 2011 and 2022). Nevertheless, considering the policy thresholds where the buffer zone mandates 60% mangrove cover on-farm, the results indicate ineffective implementation of Decision 116/1999/QD-TTg[86]. This study brings attention to the fact that the crucial role of mangrove restoration in protecting farmland and preserving farmers' livelihoods is often overlooked or not implemented, despite the increased vulnerability of farms located near open water

[84] Based on estimations of farmers of 5 integrated mangrove-shrimp farms

[85] Quyết định ban hành quy định về thực hiện chính sách bảo vệ và phát triển rừng trên địa bàn tỉnh Cà Mau do Ủy ban nhân dân tỉnh Cà Mau ban hành [Decision on the implementation of some forest protection and development policies in Ca Mau Province] No. 19/QD-UB (Sep. 22, 2010)

[86] Quyết định của thủ tướng chính phủ về việc phê duyệt quy hoạch phân vùng khôi phục rừng ngập mặn (vùng dự án) thuộc các tỉnh Cà Mau, Bạc Liêu, Sóc Trăng, Trà Vinh [Decision ratifying the zoning plan for restoratoration of submerged forests (project area) in Ca Mau, Bac Lieu, Soc Trang and Tra Vinh Provinces] No. 116/QD-TTg (May 3, 1999)

to coastal erosion. This argument emphasizes the need for farmers to learn about the risks associated with coastal erosion and the significance of mangroves in mitigating those risks.

6.4. Farmers' perspectives and insights into mangrove management

The following sections discuss various facets of the outcomes of this research related to farmers' opinions and perspectives. These include the effects of sampling on survey outcomes, the value of cultural and ecosystem services, the influence of indigenous knowledge, farmers' perceptions of mangrove cutting, and the lack of financial benefits associated with implementing mangroves on-farm.

6.4.1. Sampling effects on the survey outcomes

Limited sampling refers to using a small sample size to represent a larger population. This can increase the likelihood of Type II errors, which occur when a statistical test fails to reject a false null hypothesis. In the context of mangrove management in Vietnam, limited sampling can lead to inaccurate conclusions about the differences between Nam Can and Ca Mau forest management zones. Comparing the results of the Nam Can sample with the Ca Mau sample may not provide additional insights or information because the sample of Nam Can is included in the sample of Ca Mau. Therefore, the comparison would not be independent and could result in biased or unreliable conclusions. For example, suppose the sample size is too small. In that case, it may fail to detect significant differences in mangrove management practices between Nam Can and Ca Mau, even if such differences exist in the population. This can result in a Type II error, where the null hypothesis (that there are no differences between the two areas) is not rejected even though it should be.

In this research, the survey question analysis on the level of Nam Can in the year 2022 consisted of small samples. When looking at the results, the comparison of the production and the protection zone in Nam Can in 2022 has not shown a significant difference in the answers to either of the four questions ($P>0.05$). E.g. the insignificance of results of the questions regarding the legality of mangrove logging for construction wood could potentially be a Type II error. In this case, in 2022, fewer people in the protection zone in Nam Can thought this was legal. To mitigate the risk of Type II errors, it is important for future research to ensure a large enough sample size to detect differences that exist in the population. This can be achieved using appropriate statistical methods and sampling techniques, such as random, stratified, or cluster sampling. Using these techniques, researchers can increase the sample's representativeness and reduce the risk of Type II errors.

6.4.2. The value of (cultural) ecosystem services and indigenous knowledge

Mangrove ecosystems and their services are undervalued in current policies, which mainly focus on wood production and aquacultural production. This is problematic as mangroves can be important in mitigating climate change. Brander et al. (2012) suggest that future research should focus on the value of mangrove ecosystem services to effectively integrate them into public decision-making processes. Social-ecological resilience thinking is a holistic framework that can provide a better understanding of the complex interactions between environmental, social, and economic considerations. Previous reviews of ecosystem services assessments across Asia determined that a lack of data availability resulted in multiple effects on ecosystem services assessments (Dang et al., 2021), which may also be responsible for the lack of ecosystem services assessments focusing on cultural and supporting services (Shoyama et al., 2017). Dense mangrove patches in coastal Provinces are often fragmented due to mixed aquaculture, which may lead to severe degradation of ecological functionality and ecosystem services (Liu et al., 2020). This is an inherently complex and wicked facet of mangrove shrimp farming. Recent research has shown that integrated mangrove aquaculture might contribute less to biodiversity than speculated, as fragmentation of intact mangroves limits biodiversity effectiveness (McSherry et al., 2023).

According to the results, the respondents' level of care for mangroves decreased significantly in 2022 compared to 2011 at both the Ca Mau and Nam Can levels. The methods section emphasizes the importance of caring for mangroves, which likely refers to the quality of the mangroves and their potential to benefit the respondents' income. Successful policy implementation should integrate ecosystem services by focusing on what people care about, as Chan et al. (2012) highlighted. However, Cooper et al. (2016) found that the spiritual and aesthetic values of ecosystems, also known as cultural ecosystem services, are often disregarded, which may negatively impact decision-making effectiveness. Indigenous knowledge and valuing mangrove ecosystem services and not seeing them as a product solely could aid in the successful transition to sustainable aquaculture. Monetary conversion of the spiritual and aesthetic ecosystem services is rising; however still underdeveloped. Cultural ecosystem services pose a challenge when assigning monetary value, often being overlooked in ecosystem services planning and management. Nonetheless, these services play a vital role in the effectiveness of management strategies and decision-making processes. Their limited consideration is primarily due to their intangible and nonmaterial nature, making them pervasive yet invisible aspects of ecosystems (Chan et al., 2012).

A paper by Asia Indigenous Peoples Pact (AIPP) in 2013 discusses the importance of indigenous knowledge and participation in successful forest management and restoration. It specifically highlights the success of mangrove restoration in South Vietnam, where indigenous women played an important role in sharing their knowledge and experience of the forest and organizing and mobilizing their communities for the restoration efforts. The paper suggests that incorporating indigenous knowledge and values in forest management can lead to more sustainable and equitable outcomes (AIPP, 2013). A project led by the village forest committees of Karnataka in India has successfully protected and preserved the mangroves by using indigenous knowledge and cultural ecosystem services (Yadav, 2021). For possible ways to integrate cultural ecosystem services in ecosystem frameworks, the reader is referred to the paper of Daniel (et al., 2012).

It is important to note that the quality of mangroves is crucial for successful ecosystem restoration (for coastal protection and blue carbon storage) because degraded or low-quality mangroves may not provide the necessary ecological functions and services that healthy mangroves can offer. Decision 178 does not seem to stipulate a maximum logging amount as long as it is immediately replanted. This is quite disastrous for biodiversity and does not encourage protection but, in principle, violates the aim of forest protection. Therefore, it is important to prioritize the restoration of high-quality mangroves and implement strategies to maintain their ecological functions and services to ensure the long-term sustainability of mangrove ecosystems. Therefore, asides from the fact that farmers seem not to implement the required mangrove coverage amounts, even if they would, the focus is not on the quality of the mangrove ecosystem itself. This defies the whole purpose of mangrove restoration, and therefore future research should also emphasize how to increase the mangrove ecosystem quality.

6.4.3. Farmers' perceptions of mangrove cutting

Managing forests can be complicated due to informal arrangements and limited access to forest benefits for local farmers. Despite legal entitlement, individual owners often struggle to obtain permits for logging and cultivating forest land, leading to illegal practices. A lack of clear policies and guidance exacerbates the issue. The limited benefits offered to farmer forest owners may not incentivize them to take on forest management responsibilities (Tan, 2005). Mangrove wood used for construction purposes must be strong, durable, and resistant to moisture and pests. The wood must support the structure's weight and withstand external forces such as wind and water. Therefore, larger and mature trees are often preferred for construction purposes (Christensen et al., 2008; McEwin & McNally, 2014; Trieu et al., 2020). On the other hand, mangrove wood used for fuel does not require these same properties. It often comes from smaller trees or branches that are easier to access and cut. Due to this discreteness, it is more prone to illegal logging. The wood is used for cooking and heating in local communities, and as such, it is a readily available and affordable source of energy (Do et al., 2015; Ha, 2012a; Marchand, 2008). According to Decision 178, farmers are allowed to log mangroves for construction (following additional requirements). Farmers can log mangroves with a volume of ten m^3 anytime per unit area per three years (as per Decision 178), mangroves could be there one day whilst it is gone the next day. However, assuming a production cycle of 15 years, the chance that this happened is improbable. Looking at biomass estimations (Muhsoni et al., 2018), ten m^3 of mangroves equals around 92 m^2 of mangroves[87].

The study also reveals that farmers' perceptions of logging for construction wood differed significantly according to forest management zones in the past. However, in 2022, this was no longer the case, suggesting that the implementation of different forest management zones lacked effectiveness. The study also found similar patterns among respondents from Nam Can and Ca Mau districts, suggesting district-level management may mirror provincial-level management. However, this specific finding is not supported or refuted by existing literature, as no relevant sources could be found.

According to this research, a majority of respondents believed that fuel wood logging is legal, possibly because it can be done covertly and, therefore, is more prevalent. This perception of legality may be influenced by the implementation of Provincial Decision 19/QD-UB[88], which does not differentiate between the management of construction wood and fuel wood or between production and protection zones regarding mangrove coverage on-farms (both set at 60%). However, due to slow policy implementation and inadequate monitoring, the deduction regarding the effectiveness of this Decision is uncertain.

Vietnamese experts propose landscape-level (eco) quality standards in the Mekong Delta to allow small-scale farmers, for whom eco-certification is often not a viable option (Marschke & Wilkings, 2014), to comply with mangrove forest management obligations (Joffre et al., 2015). Assessments are often difficult to scale down because data on individual farms may not exist or may not be easily collectable. Therefore Seafood Watch implemented a risk-based sampling strategy in December 2022 to assess sustainability on the landscape-level for groups of small-scale farmers (Seafood Watch, 2022). The proposed landscape model can simplify the jurisdictional system, facilitate data collection and analysis for monitoring mangroves, and support successful restoration. Ultimately, this can improve mangrove ecosystems' health and long-term sustainability while simplifying management for small-scale farmers.

6.4.4. Lack of financial benefits of mangrove implementation on-farm

As described by the research of Pham (et al., 2013) in the Introduction, high reforestation costs and low PFES payments discourage people from (re-)planting mangroves. Forest clearing is a more viable option for farmers as economic returns are higher than PFES returns, at least before this publication in 2013. This research results show that farmers in Ca Mau and Nam Can receive more benefits from aquaculture than

[87] $(10\ m^3) \times (1000\ L/m^3) \times (0.97\ ton/100\ m^2)/\ (1.0\ ton/metric\ ton) = 97\ m^2$

[88] Quyết định ban hành quy định về thực hiện chính sách bảo vệ và phát triển rừng trên địa bàn tỉnh Cà Mau do Ủy ban nhân dân tỉnh Cà Mau ban hành [Decision on the implementation of some forest protection and development policies in Ca Mau Province] No. 19/QD-UBND (Sep. 22, 2010)

from forest exploitation. When looking at the results of 2022, it can even be claimed that even fewer respondents in the production zone benefitted from forest exploitation with aquaculture than in 2011in Ca Mau. The economic returns for replanting mangroves seem to (as of 2022) not weigh up against the economic profitability of aquaculture. This outcome is confirmed by the research of Jhaveri et al. (2018), which claims that one of the biggest hindrances in adopting the mangrove-shrimp model is that households receive limited financial gains from its implementation. Financial needs are or would not be met, and therefore, the model is only viable for large corporations with substantial economic resources (Jhaveri et al., 2018).

The survey results reveal a significant increase in the number of respondents who perceived the combination of aquaculture and forest exploitation as more beneficial in 2022 than in 2011 in Ca Mau, specifically in the production zone. This trend could imply that the value of mangroves in the market has decreased, the value of shrimp has increased, or farmers are receiving fewer benefits (from Forest Companies) than before. The respondents who received some benefits from wood exploitation were primarily located in Nam Can District, suggesting that these farmers may receive a relatively better value for wood than in the rest of the study area. These findings indicate that Ca Mau farmers may not prioritize mangrove restoration on their farms if it does not provide the economic value they require. This is in line with the research of Tinh et al. (2022), which found that farmers illegally cut down mangrove roots of mangroves to weaken or kill trees to increase their aquaculture production (Tinh et al., 2022). Even top-down legislation focuses on production instead of the ecosystem, as the crown cover currently assesses the mangrove coverage. Therefore, farmers can use more pond areas when the mangroves are planted in long strips, as less ground area is used for mangroves, and more shrimps can be bred; see Figure 44 below. This decreases the amount of mangrove trunks, decreases usable wood for construction, etcetera. The economic incentives of farmers have led to mangrove recovery on certain parts of their farms that were previously left empty without decreasing surface water areas (Lai et al., 2022). This shows how farmers, even if planting mangroves, do this with a focus on aquacultural production instead of supporting the ecosystem.

Figure 44 Mangrove tree crown

6.5. Wickedness

This master research undertaking image analysis, policy analysis, and assessing farmers' perceptions and estimations of mangrove cover has made significant strides in reducing the wickedness of the problem of ineffective mangrove forest management on-farms in Ca Mau.

Firstly, the research has enhanced our understanding of the intricate interactions between top-down management and farmers in implementing mangroves on-farm. By performing remote sensed-based manual image analysis on two satellite images and analysing the results, it was possible to compare the changes within different mangrove forest zoning areas. This comparison revealed a lack of significant differences in mangrove management on-farm between the policy zones, highlighting the ineffectiveness of the current policy. This understanding contributes to a better grasp of the factors contributing to the wicked problem.

Secondly, by examining farmers' perceptions and analysing policy options, the research has identified key obstacles and potential solutions rooted in the local context of on-farm management. For instance, the research has shed light on specific challenges farmers face in adopting sustainable practices, including lack of care about mangroves, financial constraints, and limited knowledge about the legality of sustainable management techniques like mangrove logging. By comprehending these challenges, policymakers and researchers can develop targeted interventions that address the specific needs of farmers, ultimately increasing the likelihood of sustainable and resilient aquacultural systems capable of tackling environmental and economic challenges.

Thirdly, the dissemination of research findings and active engagement with local communities, policymakers, and other stakeholders have played a crucial role in raising awareness about the problem and garnering support for potential solutions. Field visits have provided an in-depth understanding of the realities on the ground, including farmers' perspectives and motivations for managing their farms. Since farmers are primary stakeholders with firsthand experience in sustainable management practices, involving them in the design and implementation of such practices allows for identifying barriers to adoption, collaborative solution-building, and establishing trust and collaboration. The research findings have been shared with fellow students, researchers, and field experts through presentations and knowledge-sharing initiatives. Furthermore, the research will be disseminated via online platforms such as LinkedIn and the University of Twente's Academic Output Platform and shared with students from Can Tho University, facilitating broader awareness of the effectiveness of the current policy zones.

Additionally, remote sensing-based assessments offer technical opportunities for transparent, frequent, and accurate monitoring of mangroves on shrimp farms compared to current methods. These assessments provide enhanced spatial coverage, enabling a comprehensive understanding of mangrove extent and distribution. The high temporal resolution allows for the detection of short-term trends and the impacts of human activities. Objective and quantitative analysis utilizing algorithms and vegetation indices minimizes biases and facilitates standardized monitoring. Advanced image processing and integrating multiple remote-sensing data sources improve accuracy and precision. In addition, the transparency and accessibility of data enable independent verification and collaborative decision-making processes, fostering effective mangrove conservation and management.

Lastly, the research's analysis of the effectiveness of mangrove forest management zones and other regulations provides valuable insights into the problem and potential solutions, thereby supporting evidence-based decision-making. The research can inform and inspire action by disseminating the research findings to relevant stakeholders, including policymakers, community leaders, NGOs, and academics, through various means such as reports, presentations, workshops, and online platforms. Establishing connections with local communities during field visits facilitates the sharing of research, potentially aiding in the successful implementation of alternative approaches to mangrove management policies. Furthermore, publicly sharing the research on platforms like ITC's sharing platform and LinkedIn can raise awareness and foster discussion on the topic.

Overall, the knowledge of this wicked problem became more certain (Georgiadou & Reckien, 2018). This research has significantly contributed to reducing the problem's wickedness by deepening our understanding of the complexities involved, identifying barriers and potential solutions, engaging stakeholders, utilizing advanced monitoring techniques, and providing evidence-based insights for informed decision-making.

7. CONCLUSION

This wicked research uncovers significant issues regarding the coherence and overlap of policies implemented for managing mangrove forests across various forest management zones. These findings highlight the need for a streamlined approach. The current legislation fails to effectively distinguish between the obligations of mangrove management practices in production and protection zones. This lack of clarity is supported by remote sensing-based image analysis, which reveals a significant increase in mangrove coverage between 2011 and 2019 but no discernible difference between the policy zones. Furthermore, farmers' opinions corroborate this lack of differentiation, which showed a lack of differentiation between the different forest management zones in 2022 compared to 2011 in their perceptions regarding the illegality of logging for construction wood. Finally, the farmers' overestimations of on-farm mangrove cover indicate a flawed assessment of mangrove presence. Additionally, the farmers' perceptions reflect limited financial benefits from mangrove replanting compared to aquaculture activities. Considering these factors, it is imperative to address these issues to mitigate adverse consequences such as carbon exhaustion and erosion.

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8. APPENDICES

APPENDIX A – Overview of ministries

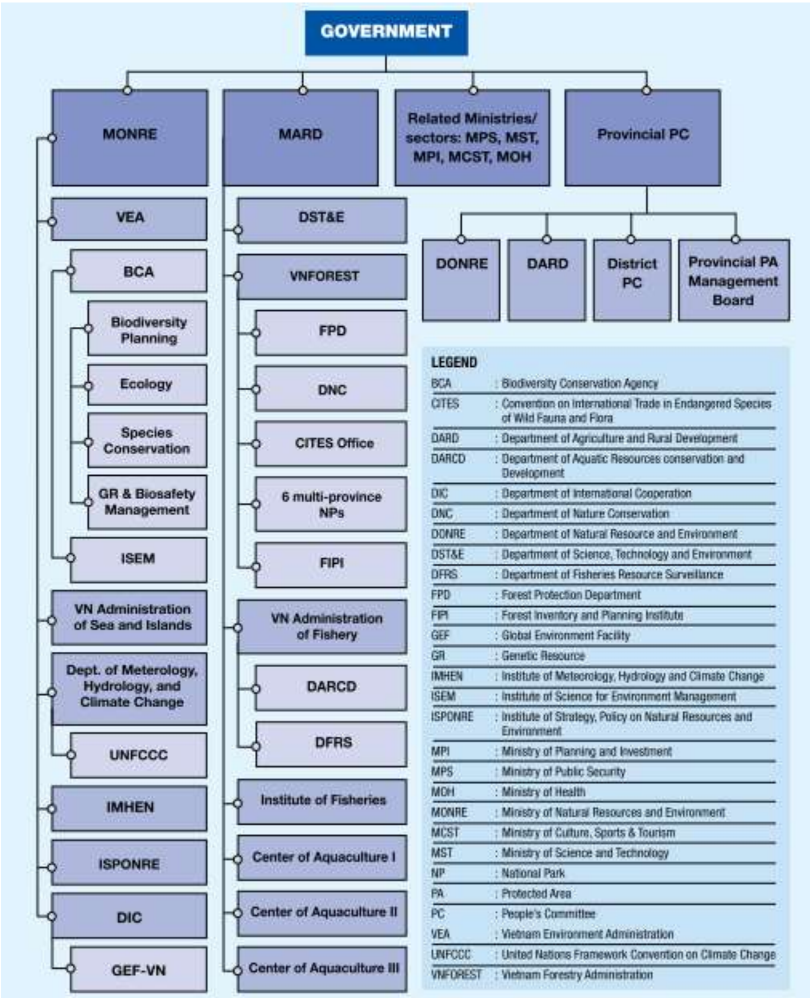


Figure 45 Organizational structure of biodiversity state management (adapted from MONRE, 2013)

APPENDIX B – ERDAS Imagine rectification

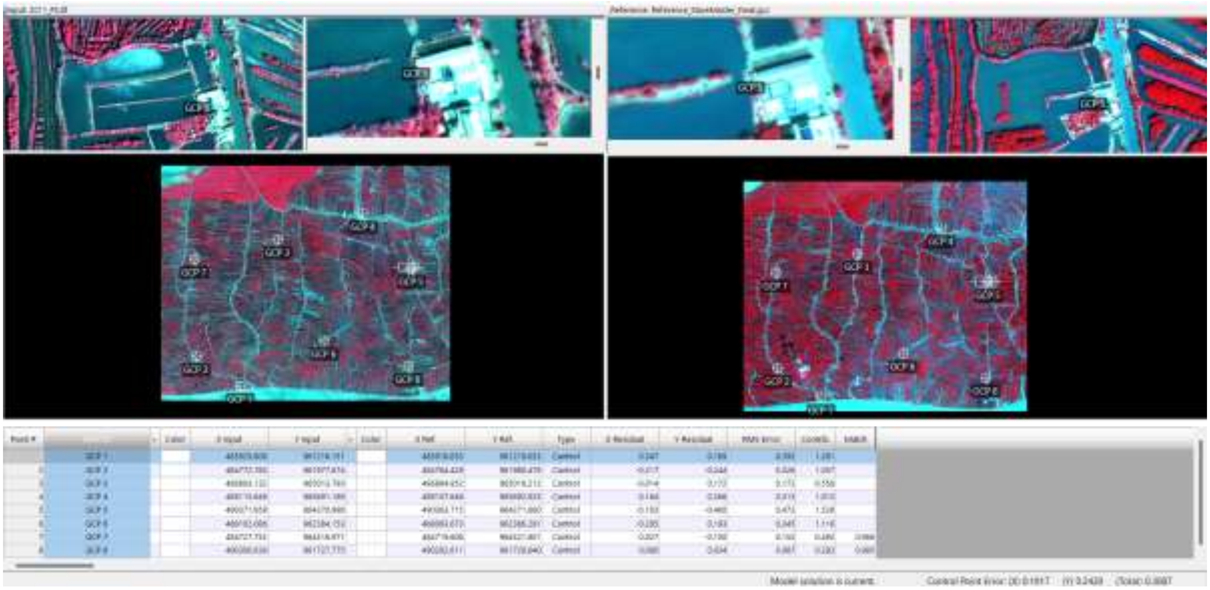


Figure 46 ERDAS Imagine Master-Slave and GCP's

APPENDIX C – Mangrove height requirements by shadow calculations

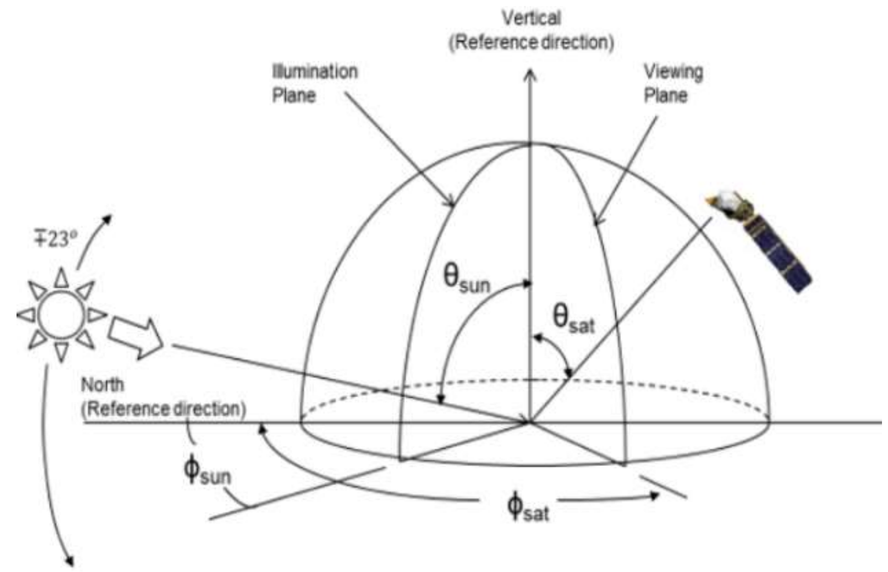


Figure 47 Sattelite and sensor angles (adapted from the United States Geological Survey, n.d.)

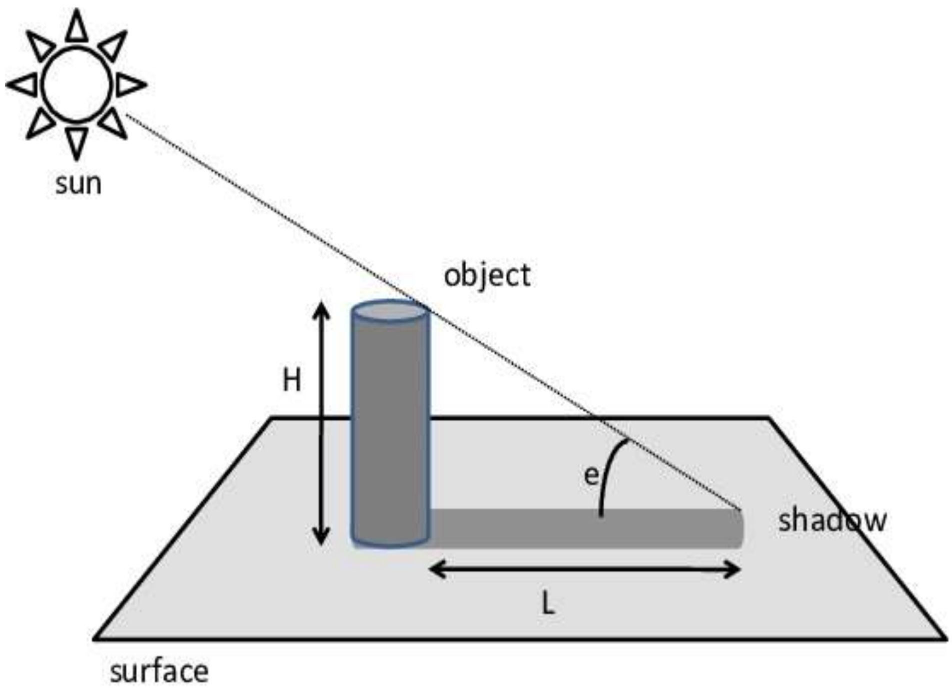


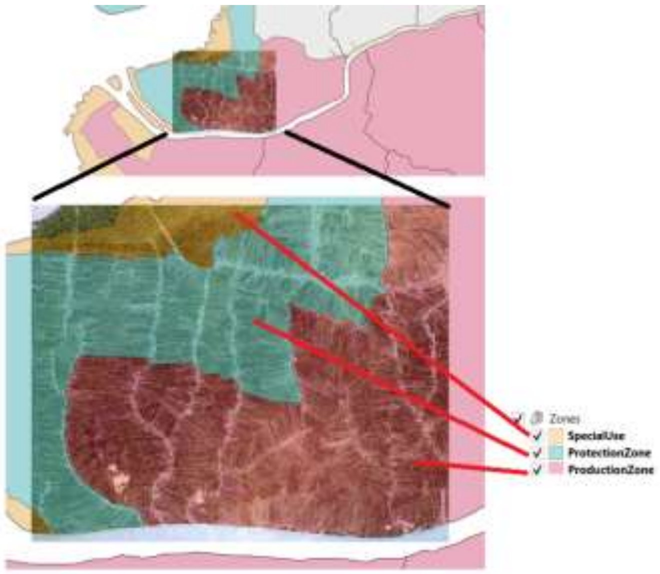
Figure 48 Sun angle (e), object height (H) and shadow length (L) (adapted from Sandnes, 2011)

APPENDIX D – Instruction sheet data collection

Summary

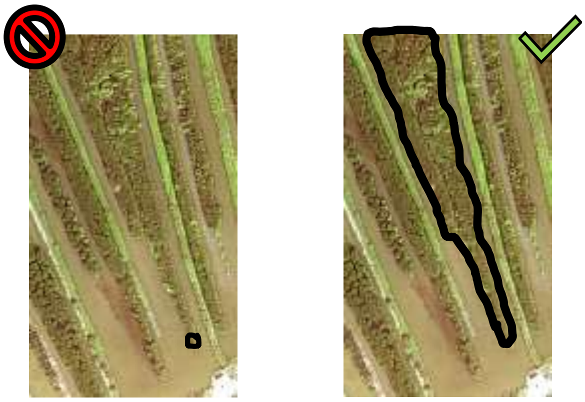
Hereby a small overview of what we discussed previously on how to gather the data I need for my MSc Research. My topic is on the mangrove coverage change per shrimp farm, comparing 2011 to 2019 remotely sensed datasets. Within this I compare the results of mangrove coverage change in the different Zonation Areas in my study Area. And for this I need a dataset for classification and verification. This is what you will be doing, thank you all!

Study area and three mangrove forest zoning areas.



In the field

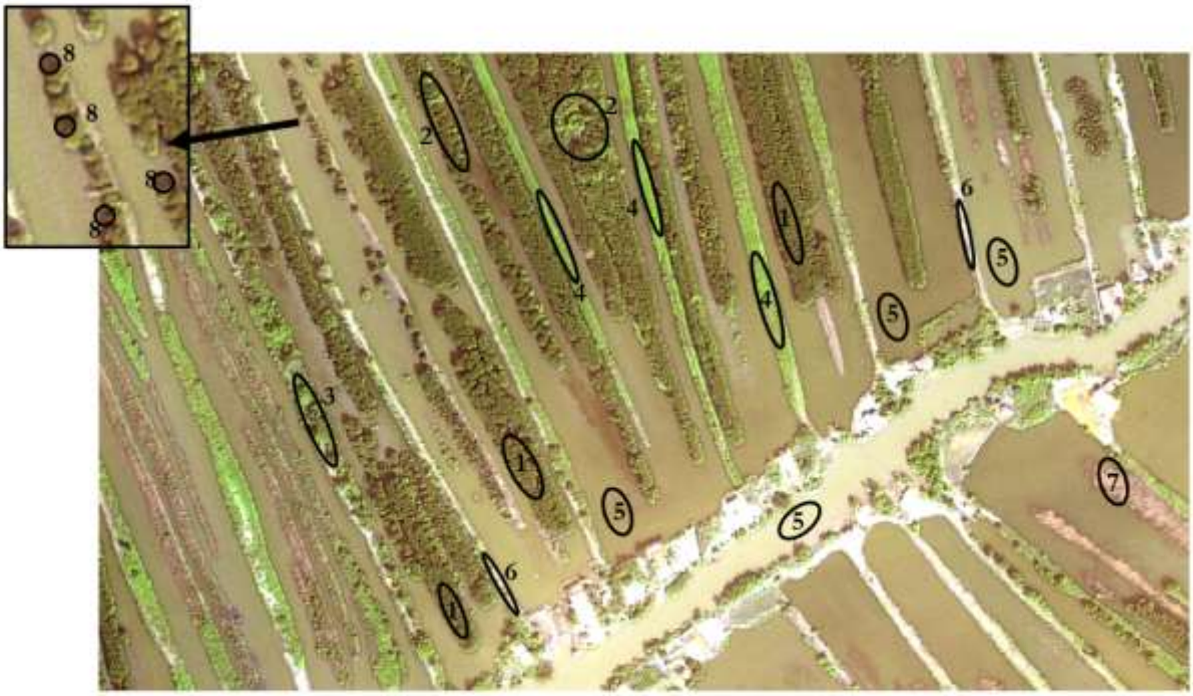
Look at segments! When determining a class, do not look at one point but verify the whole segment as good as possible (Class 8 is the only class which is point sampling); see images below. Don't classify based on points, do classify based on segment



Classes

In total I created four main classes and 4 *extra* classes. The goal is to sample at least 20 segments of Class 1, 2, 3, 4. And at least 15 segment samples of Class 5,6,7 and at least 15 point samples of Class 8. Make sure to note down everything (mixed species and/or ages) in the remarks section in the observation sheet and take photos of the sample sites (write down to which coordinates the photos belong). Make sure you know very clearly where the sample class is measured, so that you can put it in a new layer in the attached GIS file.

Open the .tif map and search the location (lon lat) of the class sampled in the field and insert the measured data as a new layer in the map (same CRS).



Preliminary Class Code	Visual Characteristics
1	Strip dark green course texture (not touching shrimp farm boundary)
2	Strip mixed dark and light green course texture (not touching shrimp farm boundary)
3	Long and narrow mixed dark and light green feature (touching shrimp farm boundary)
4	Long and narrow light green fine texture (touching shrimp farm boundary)
5	Smooth, brownish green to very light brownish green
6	White and smooth
7	Red/purple, course texture
8	Black or nearly black along the north-western side of another segment

Field class code	Description
A	Mangroves, mono species/ages
B	Mangroves, mixed species/ages
C	Dike with only grass
D	Dike mixed with trees, shrubs, herbs, and grass
E	Water
F	Sand
G	Mud
One of the above	In a segment with number 8

APPENDIX E – Classification method validation

Table 20 Method classification validation 2011 to 2019. FCC: Field classification class. Changes in classification categorized in decrease (D), increase (I), neutral/stagnation (N) (in mangrove cover), not possible (X)

2011	2019	Fcc 11-19	Decrease, increase, neutral, not possible
Mixed mangrove	Mixed mangrove	A1	N
Mixed mangrove	Dark mangrove	A2	N
Mixed mangrove	Mud	A3	D
Mixed mangrove	Mud with mangrove propagule	A4	D
Mixed mangrove	Water	A5	D
Mixed mangrove	Dike trees grass	A6	D
Mixed mangrove	Dike trees	A7	D
Mixed mangrove	Dike grass	A8	D
Dark mangrove	Mixed mangrove	B1	N
Dark mangrove	Dark mangrove	B2	N
Dark mangrove	Mud with mangrove propagule	B3	D
Dark mangrove	Mud with mangrove propagule	B4	D
Dark mangrove	Water	B5	D
Dark mangrove	Dike trees grass	B6	D
Dark mangrove	Dike trees	B7	D
Dark mangrove	Dike grass	B8	D
Mud	Mixed mangrove	C1	I
Mud	Dark mangrove	C2	X
Mud	Mud	C3	N
Mud	Mud with mangrove propagule	C4	I
Mud	Water	C5	N
Mud	Dike trees grass	C6	N
Mud	Dike trees	C7	N
Mud	Dike grass	C8	N
Mud with mangrove propagule	Mixed mangrove	D1	I
Mud with mangrove propagule	Dark mangrove	D2	I
Mud with mangrove propagule	Mud	D3	D
Mud with mangrove propagule	Mud with mangrove propagule	D4	N
Mud with mangrove propagule	Water	D5	D
Mud with mangrove propagule	Dike trees grass	D6	D
Mud with mangrove propagule	Dike trees	D7	D
Mud with mangrove propagule	Dike grass	D8	D
Water	Mixed mangrove	E1	I
Water	Dark mangrove	E2	X
Water	Mud	E3	N
Water	Mud with mangrove propagule	E4	I
Water	Water	E5	N
Water	Dike trees grass	E6	N
Water	Dike trees	E7	N
Water	Dike grass	E8	N
Dike trees grass	Mixed mangrove	F1	I
Dike trees grass	Dark mangrove	F2	X
Dike trees grass	Mud	F3	N
Dike trees grass	Mud with mangrove propagule	F4	I
Dike trees grass	Water	F5	N
Dike trees grass	Dike trees grass	F6	N
Dike trees grass	Dike trees	F7	N
Dike trees grass	Dike grass	F8	N
Dike trees	Mixed mangrove	G1	I
Dike trees	Dark mangrove	G2	X
Dike trees	Mud	G3	N
Dike trees	Mud with mangrove propagule	G4	I
Dike trees	Water	G5	N
Dike trees	Dike trees grass	G6	N
Dike trees	Dike trees	G7	N
Dike trees	Dike grass	G8	N
Dike grass	Mixed mangrove	H1	I
Dike grass	Dark mangrove	H2	X

Table 21 Method classification validation 2019 to 2022. FCC: Field classification class. Changes in classification categorized in decrease (D), increase (I), neutral/stagnation (N) (in mangrove cover), not possible (X)

2019	2022	Fcc 19-22	Decrease, increase, neutral, not possible
Mixed mangrove	Mixed mangrove	A1	N
Mixed mangrove	Dark mangrove	A2	I
Mixed mangrove	Mud	A3	D
Mixed mangrove	Mud with mangrove propagule	A4	D
Mixed mangrove	Water	A5	D
Mixed mangrove	Dike trees grass	A6	D
Mixed mangrove	Dike trees	A7	D
Mixed mangrove	Dike grass	A8	D
Dark mangrove	Mixed mangrove	B1	N
Dark mangrove	Dark mangrove	B2	N
Dark mangrove	Mud	B3	D
Dark mangrove	Mud with mangrove propagule	B4	D
Dark mangrove	Water	B5	D
Dark mangrove	Dike trees grass	B6	D
Dark mangrove	Dike trees	B7	D
Dark mangrove	Dike grass	B8	D
Mud	Mixed mangrove	C1	X
Mud	Dark mangrove	C2	X
Mud	Mud	C3	N
Mud	Mud with mangrove propagule	C4	I
Mud	Water	C5	N
Mud	Dike trees grass	C6	N
Mud	Dike trees	C7	N
Mud	Dike grass	C8	N
Mud with mangrove propagule	Mixed mangrove	D1	X
Mud with mangrove propagule	Dark mangrove	D2	X
Mud with mangrove propagule	Mud	D3	D
Mud with mangrove propagule	Mud with mangrove propagule	D4	N
Mud with mangrove propagule	Water	D5	D
Mud with mangrove propagule	Dike trees grass	D6	D
Mud with mangrove propagule	Dike trees	D7	D
Mud with mangrove propagule	Dike grass	D8	D
Water	Mixed mangrove	E1	X
Water	Dark mangrove	E2	X
Water	Mud	E3	N
Water	Mud with mangrove propagule	E4	I
Water	Water	E5	N
Water	Dike trees grass	E6	N
Water	Dike trees	E7	N
Water	Dike grass	E8	N
Dike trees grass	Mixed mangrove	F1	X
Dike trees grass	Dark mangrove	F2	X
Dike trees grass	Mud	F3	N
Dike trees grass	Mud with mangrove propagule	F4	I
Dike trees grass	Water	F5	N
Dike trees grass	Dike trees grass	F6	N
Dike trees grass	Dike trees	F7	N
Dike trees grass	Dike grass	F8	N
Dike trees	Mixed mangrove	G1	X
Dike trees	Dark mangrove	G2	X
Dike trees	Mud	G3	N
Dike trees	Mud with mangrove propagule	G4	I
Dike trees	Water	G5	N
Dike trees	Dike trees grass	G6	N
Dike trees	Dike trees	G7	N
Dike trees	Dike grass	G8	N
Dike grass	Mixed mangrove	H1	X
Dike grass	Dark mangrove	H2	X

APPENDIX F – Survey questions

Code:....................................

Surveyor: .... Date: ...../...../2010

Coordinates (UTM48N-WGS-84): X: .... Y: ....

Household's name: .... ☐ 1. Householder ☐ 2. Member

Age:.................. Sex: ☐ 1. Male ☐ 2. Female

Education level: ....

Experiences on mangrove management: ..... years

Address: Village .... District: .... Province: ....

Q1. How many members in your family?

		Q11	Q12	Q13	Q14	Q15	Q16		Q17
Order	Full name	Sex (*)	Age	Education level	Status (**)	Position (#)	Job (@)		Where to work (~)
							Major	Minor	

Note: (*) : 1. Male; 2. Female

(**): 1. Study; 2. Retied; 3. Depend on other people

(#): 1. Householder; 2. Member

(@): 1. Famer; 2. Fisherman; 3. Government officer, 4.Trade; 5. Jobless

(~): 1. In village; 2. in District; 3. Other districts or provinces

Q2. Land use information

Code	LUT (*)	Area (ha)	Percentage (**)	Altitude (***)	Sources	
					Succession	Buy
Q21	Total area					
Q22	Mangrove					
Q23	Aquaculture					
Q24	Vegetation					
Q25	Other forest					
Q26	Residential					
Q27	Others					

Notes: (*): Land use type; (**): Percentage per total area ; (***)1. High; 2. Medium; 3. Low

Q3. Understanding

Q31. What do you understand by the term mangrove? (definition)

Q32. Which mangrove species do you know in your land?

1. Mắm trắng (Avicennia alba);
2. Mắm biển (Avicennia marina);
3. Đước đôi (Rhizophora apiculata)
4. Dừa nước (Nipa fruticans)
5. Others: (Local name)
   ....
6. Mắm đen (Avicennia officinalis);
7. Mắm quăn (Avicennia lanata);
8. Đưng (*Rhizophora mucronata)*
9. Chà là (Pheonix paludosa)

Q33. Do the mangroves have a particular function?

1. Wind break 2. Wave break 3. Water break

4. Barrier 5. Storm protection 6. Others

Q34. Have you been taught about function of mangrove by your parents/teachers?
1. Yes 2. No

Q35. Do the mangroves have an economic value?
1. Yes 2. No

Q36. How important are the mangroves for your livelihood?
1. Very important 2. Little important 3. Not at all 4. Don't know

Q37. Do you think that cutting down the mangroves will reduce your income?
1. Yes 2. No

Q4. Protection

Q41. Is mangrove related products a major part of your income?
1. Yes 2. No

Q42. How much percent of your household income is related to mangrove?
1. Almost all 2. More than 50% 3. Less than 50% 4. Less than 30%
5. Non

Q43. How much you think would be one hectare of land full of mangrove?
……………………………(VND)

Q44 Are mangrove worth to be protected

1. No I don't think so
2. Yes I think so
3. I don't know

Q45. It will be better in my area if more mangroves are cut down and we have more space for aquacultures

Q46. I will be better in my area if more mangroves will be planted
1. Agree 2. Disagree

Q47. I know that mangroves have a protection value, but I cannot make money with them
1. Agree 2. Disagree

Q48. I have observed that decrease in mangroves led to more coastal erosion
1. Yes 2. No

Q49. Fish variety in mangrove areas is larger than in areas without mangroves
1. Agree 2. Disagree

Q411. Mangroves hinder my smooth moving (by boat)
1. Yes 2. No

Q412. I actually do not care about mangroves
1. Agree 2. Disagree

Q413. If all mangroves in the Mekong Delta disappear, it will not have a big effect
1. Agree 2. Disagree

Q414. If there are no mangroves, maybe there will be a bit more shore erosion, but I do not mind
1. Agree 2. Disagree

Q415.I would love to have more mangroves in and around of my village
1. Agree 2. Disagree

Q416.Toursiam plays a role in my region
1. Agree 2. Disagree

Q5. Utilization

51. General uses of mangrove

Q511. Do you use mangroves for any purpose?
1. Yes 2. No

Q512. Do mangroves play a role in your life?
1. Not at all 2. Some times 3. Very much

Q513. What are the positive aspects of mangroves

Q514. What are the negative aspects of mangroves

Q515. What are your main uses of mangroves?

1. Fuel (wood, charcoal)
2. Construction (house, fence, furniture, utensils)
3. Medicinal
4. Chemical (dyes, poisons)
5. Food (honey, alcohol, animal feed)
6. Fishing
7. Recreation purposes (resting, tourism)
8. Others………

Q516. How far do you travel to collect the above (Q42)?
…………….km

Q517. Do you benefit more from mangrove wood or from mangrove aquaculture resources?
1. Wood 2. Aquaculture 3. Both 4. Don't know

Q518. Do you know other subsistence uses of mangroves?

1. Yes (which one?)………………………………………………………………………………

2. No 3. Don't know

Q519. Do you know other subsistence uses of mangroves?
----

52. Uses of mangrove for construction

Q521. Do you use mangroves wood for construction and service wood?
1. Yes 2. No

Q522. What do you use fuel wood for?

Q511. Do you use mangroves for any purpose?
1. Yes 2. No

Q512. Do mangroves play a role in your life?
1. Not at all 2. Some times 3. Very much

Q513. What are the positive aspects of mangroves
....
....

Q514. What are the negative aspects of mangroves
....
....

Q515. What are your main uses of mangroves?

1. Fuel (wood, charcoal)
2. Construction (house, fence, furniture, utensils)
3. Medicinal
4. Chemical (dyes, poisons)
5. Food (honey, alcohol, animal feed)
6. Fishing
7. Recreation purposes (resting, tourism)
8. Others…………………………………………………………………………… ………………………………………………………………………………………… ……………………

Q516. How far do you travel to collect the above (Q42)?
…………….km

Q517. Do you benefit more from mangrove wood or from mangrove aquaculture resources?
1. Wood 2. Aquaculture 3. Both 4. Don't know

Q518. Do you know other subsistence uses of mangroves?

1. Yes (which one?)…………………………………………………………………………

2. No 3. Don't know

Q519. Do you know other subsistence uses of mangroves?
....
....

52. Uses of mangrove for construction

Q521. Do you use mangroves wood for construction and service wood?
1. Yes 2. No

Q522. What do you use fuel wood for?

1. Construction wood (housing and fencing)
2. Service wood (furniture, wood carving)

Q523. What species of mangrove do you use for construction?

Species	Part used	Use	
1.			CW/SW
2.			CW/SW
3.			CW/SW
4.			CW/SW
5.			CW/SW

Q524. How do you get the mangrove wood?

1. Buy: for how much?...............................(VND). (if you don't have mangrove)
2. Receive from neighbors
3. Exchange for service
4. Personal collection

Q525. If personal collection, how frequently do you visit the mangrove?

-……………………./week

-……………………./month

-whenever you need

Distance for time travelled: -…………….km; -………………….hour

Q526. Do you sell mangrove wood products for others?

1. Yes 2. No

For how much?.......................................(VND)

Which one?...

Q527. Do you think this construction wood extraction in your land is allowed (legally)?
1. Yes 2. No 3. Don't know

53. Uses of mangrove for firewood and charcoal

Q531. Do you use mangrove wood from your land for firewood and charcoal?
1. Yes 2. No

Q532. What do you use mangrove wood for?
1. Cooking 2. Heating 3. Other

Q533. What species of mangroves do you use for wood products? (F: firewood; C: Charcoal)

Species	Part used	Use	
1.			F/C
2.			F/C
3.			F/C

4.			F/C
5.			F/C

Q534. How do you get the mangrove wood?

1. Buy: for how much?...............................(VND). (if you don't have mangrove)
2. Receive from neighbors
3. Exchange for service
4. Personal collection

Q535. If personal collection, how frequently do you visit the mangrove?

-……………………../week

-……………………../month

-whenever you need

Distance for time travelled: -……………..km; -…………………..hour

Q536. Do you sell mangrove wood products for others?

1. Yes 2. No

For how much?.....................................(VND)

Which one?...

Q537. Do you think this fuelwood extraction in your land is allowed (legally)?
1. Yes 2. No 3. Don't know

Q538. Apart from mangrove firewood and charcoal, which other resources of fuel do you use?
1. Gas 2. Electricity 3. Other firewood ………………………………………

Q539. Would you replace the mangrove wood resource you use as fuelwood by another?
1. Yes 2. No

54. Uses of mangrove combined with aquaculture

Q541. Do you combined mangrove with aquaculture?
1. Yes 2. No

Q542. How is the ratio of mangrove and aquaculture?

1. 40% mangrove, 60% aquaculture
2. 60% mangrove, 40% aquaculture
3. 30% mangrove, 70% aquaculture
4. 100% aquaculture
5. 100% mangrove
6. Other ratio………………………………

Q543. How is your land looks like (draw by themselves)

Q544. How is your income base on your total area?

1………………m² for aquaculture 2………………………m² for mangrove

Q545. Income from aquaculture productions

Q546.(*) : What do you fish?

Q547.(**): Where do you fish?

Q548.(#): For what purposes is it used?

Q549.(@): Has the fishing pattern (species and quantity) changed over time?

Q.5411(~): Do you think this change is related to a change of mangrove?

Species(*)	Quantity (kg)	Location(**)	How long (moth)	For what purpose(#)	Market prices (VND/kg)	Production change over time(@)	Because change of mangrove are(~)

Note: (*) : 1. Fish; 2. Shrimp; 3. Crab; 4. Other……………

(**): 1. Inside your land; 2. Outside;

(#): 1. Subsistence; 2. Sell; 3. Both

(@): 1. Increase; 2. Decrease; 3. No change

(~): 1. No; 2. Yes; 3.

How?……………………………………………………………………………………

Q6. Investment of Aquaculture

Q61.(*) : What do you grow?

Q62.(**): How many day do you spend for pond preparation?

Q63.(#): What do you feed them?

Q64.(@): How much do you have to pay for ?

Q65.(~): How many month you need for one crop?

Species(*)	Seed/breed (kg)	Land preparation(**) (day)	Feed(#) (kg)	Prices (VND) (@)	How long (month) (~)	Total investment (VND)

Note: (*) : 1. Fish; 2. Shrimp; 3. Crab; 4. Other……………

(**): 1. Manpower; 2. Mechanical ; 3. Not at all

(#): 1. Not at all (natural food); 2. Everyday; 3. How many times per crop?....................

(@): 1. Your own power; 2. Hire;

The end

APPENDIX G – Survey code

```r
#clear environment ----
rm(list = ls(all = TRUE))
graphics.off()
shell("cls")

# set up: ----
library(readxl)
library(raster)
library(sp)
library(carData)
library(ggplot2)
library(caTools)
library(agricolae)
library(tidyverse)
library(datarium)
library(ggpubr)
library(rstatix)
require(ggplotr)
library(ggpubr)
library(dplyr)
library(janitor)
library(vtree)
library(CGPfunctions)
library(skimr)
library(tidyverse)
library(sjPlot)
library(likert)
library(lme4)
library(lmerTest)
setwd("C:\\Users\\jhoge\\OneDrive\\Documenten\\Data_Processing\\Survey")

# load data : ----
data_22 <- read_excel("Survey_Data_Final.xlsx", sheet = 'SD_2022_Final')
data_11 <- read_excel("Survey_Data_Final.xlsx", sheet = 'SD_2011_Final')
data_22 <- replace(data_22, data_22=='', NA)
data_11 <- replace(data_11, data_11=='', NA)
data_22$Zoning = as.factor(data_22$Zoning)
data_11$Zoning = as.factor(data_11$Zoning)
data_11$Year = as.factor(data_11$Year)
data_22$Year = as.factor(data_22$Year)
data_11$Disct = as.factor(data_11$Disct)
data_22$Disct = as.factor(data_22$Disct)

#Select variable to Analyze ----
data_22$Answer = as.factor(data_22$INC)
data_11$Answer = as.factor(data_11$INC)
tabyl(data_11, Zoning, Answer)
tabyl(data_22, Zoning, Answer)

#Data  over Years ----
data_11_sel<-data_11[,c("Year", "Zoning","Disct","NEAR_DIST", "Answer")]
data_22_sel<-data_22[,c("Year", "Zoning","Disct","NEAR_DIST", "Answer")]

#Drop NA and DK Rows----
data_11_sel <- data_11_sel[!(is.na(data_11_sel$Answer) | data_11_sel$Answer==""), ]
data_11_sel <- data_11_sel[data_11_sel$Answer != "DK",]
data_11_sel$Answer <- droplevels(data_11_sel$Answer)
data_22_sel <- data_22_sel[!(is.na(data_22_sel$Answer) | data_22_sel$Answer==""), ]
data_22_sel <- data_22_sel[data_22_sel$Answer != "DK",]
data_22_sel$Answer <- droplevels(data_22_sel$Answer)
tabyl(data_11_sel, Zoning, Answer)
tabyl(data_22_sel, Zoning, Answer)

#merge datafiles ----
Data <- rbind(data_11_sel,data_22_sel)

#view_df(data_11, show.frq = T, show.prc = T, show.na =T)


#write Code Titles ----
a <- "Are mangroves worth protection? 2011 vs. 2022"
b <- "Are mangroves worth protection?"
c <- "Are mangroves worth protection? vs. Production Zone"
g <- "Are mangroves worth protection? vs. Protection Zone"
d <- "Are mangroves worth protection? vs. Forest Management Zones 2011"
e <- "Are mangroves worth protection? vs. Forest Management Zones 2022"
f <- "Are mangroves worth protection? vs. District 2011"
h <- "Are mangroves worth protection? vs. District 2022"

# Data t vs T----
sjPlot::tab_xtab(var.row = Data$Year, var.col = Data$Answer, title = a,
                 show.row.prc = TRUE)
sjPlot::plot_xtab(Data$Year,Data$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE, legend.title = a,
                   coord.flip = TRUE)

# Zone sig diff a-A----
pd <- Data[Data$Zoning == "Production", ]
sjPlot::tab_xtab(var.row = pd$Year, var.col = pd$Answer, title = c, drop.empty = TRUE,
                 show.row.prc = TRUE)
sjPlot::plot_xtab(pd$Year,pd$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE, legend.title = c,   coord.flip = TRUE)

# Zone sig diff b-B----
pt <- Data[Data$Zoning == "Protection", ]
sjPlot::tab_xtab(var.row = pt$Year, var.col = pt$Answer, title = g,
                 show.row.prc = TRUE)
sjPlot::plot_xtab(pt$Year,pt$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE, legend.title = g,   coord.flip = TRUE)

# Data 2011 sig diff a-b  ----
sjPlot::tab_xtab(var.row = data_11_sel$Zoning, var.col = data_11_sel$Answer, title = d,
                 show.row.prc = TRUE)

sjPlot::plot_xtab(data_11_sel$Zoning, data_11_sel$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE, legend.title = d, coord.flip = TRUE)
```

```
# Data 2022 sig diff A-B   ----
sjPlot::tab_xtab(var.row = data_22_sel$Zoning, var.col = data_22_sel$Answer, title = e,
                 show.row.prc = TRUE)

sjPlot::plot_xtab(data_22_sel$Zoning, data_22_sel$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE, legend.title = e,
               coord.flip = TRUE)

#District Level ----
NamCan <- Data[Data$Disct == 'Nam Can',]
NamCan <- droplevels(NamCan)

NamCanpd <- NamCan[NamCan$Zoning == 'Production', ]
NamCanpt <- NamCan[NamCan$Zoning == 'Protection', ]
NamCan11 <- NamCan[NamCan$Year == '2011', ]
NamCan22 <- NamCan[NamCan$Year == '2022', ]

tabyl(NamCanpd, Year, Answer)
tabyl(NamCanpt, Year, Answer)

#d-D ----
sjPlot::plot_xtab(NamCan$Year, NamCan$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE , legend.title = f,
                 coord.flip = TRUE)
#ad-AD ----
sjPlot::plot_xtab(NamCanpd$Year, NamCanpd$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE , legend.title = f,
                  coord.flip = TRUE)
#bd-BD ----
sjPlot::plot_xtab(NamCanpt$Year, NamCanpt$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE , legend.title = f,
                  coord.flip = TRUE)
#aD vs bD ----
sjPlot::plot_xtab(NamCan11$Zoning, NamCan11$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE , legend.title = f,
                  coord.flip = TRUE)
#AD vs BD ----
sjPlot::plot_xtab(NamCan22$Zoning, NamCan22$Answer, margin = "row", bar.pos = "stack",
                  drop.empty = TRUE, show.summary = TRUE , legend.title = f,
                  coord.flip = TRUE)
```

APPENDIX H – Mangrove classification discrepancies

GDLA land use classification	
1	Agriculture
1.1	Agriculture production land
1.2	Forestry land
1.2.1	Production forest
1.2.2	Protection forest
1.2.3	Special-uses forest
1.3	Aquaculture land
1.4	Salt production
1.5	Other agriculture land
2	Non-agriculture land
3	Unused land
4	Coastal wetland (observed)

Forest land in both categories

FPD: Forest land without forest

GLDA: Unused land

Other land uses

FPD land use classification	
I	Forest
A	Natural forest
A1	Forest (wood stock)
A2	Bamboo forest
A3	Mixed forest
A4	Mangrove forest
A5	Rock mountain forest
B	Planted forest
B1	Planted forest (w/wood stock)
B2	Planted forest (w/o wood stock)
B3	Bamboo forest for production
B4	Specialty tree
II	Bare land, mountain without forest
C1	Ia (grass, cane)
C2	Ib (scattered brush, tree, bamboo)
C3	Ic (a lot of re-growth wood trees)
C4	Rock mountain without forest
C5	Sandbanks, swamps etc.
III	Other land

Figure 49 Classification of General Department of Land Administration versus Forest Protection Department Classification (adapted from Pham et al., 2012)

APPENDIX I – Results manual segmentation

Table 22 Result of manual delineation. Class percentages, shrimp farm area in 2011 and 2019 and change.

	ID	Shrimp farm area (m^2)	2011 (%)			2019 (%)			Mangrove change (%)
			Mangrove	Propagule	Other	Mangrove	Propagule	Other	
Production zone	1	41750	43.5%	0.0%	56.5%	43.4%	0.0%	56.6%	-0.15%
	2	39803	42.2%	1.0%	56.8%	70.4%	0.0%	29.6%	28.11%
	3	35448	19.5%	0.0%	80.5%	13.2%	14.4%	72.3%	-6.22%
	4	42486	35.0%	0.7%	64.2%	53.2%	0.0%	46.8%	18.16%
	5	25610	37.2%	0.3%	62.5%	28.0%	2.3%	69.7%	-9.13%
	6	37982	36.6%	0.0%	63.4%	10.3%	17.8%	71.9%	-26.35%
	7	27750	7.2%	0.3%	92.6%	24.9%	0.5%	74.6%	17.73%
	8	162062	37.6%	0.0%	62.4%	18.0%	0.2%	81.9%	-19.61%
	9	77053	13.8%	4.2%	82.0%	30.7%	0.0%	69.3%	16.94%
	10	33128	7.9%	2.3%	89.7%	29.6%	0.5%	69.9%	21.64%
	11	25198	10.7%	0.0%	89.3%	45.0%	0.0%	55.0%	34.31%
	12	44529	32.6%	0.0%	67.4%	2.5%	5.6%	92.0%	-30.19%
	13	45422	9.8%	4.0%	86.1%	30.1%	0.0%	69.9%	20.24%
	14	43801	10.1%	0.0%	89.9%	24.8%	0.3%	74.9%	14.69%
	15	63435	9.2%	0.0%	90.8%	17.8%	3.4%	78.7%	8.65%
	16	71280	24.8%	0.0%	75.2%	44.2%	0.0%	55.8%	19.39%
	17	32195	30.3%	0.0%	69.7%	32.6%	0.0%	67.4%	2.28%
	18	63795	20.1%	0.0%	79.9%	12.3%	0.7%	87.0%	-7.86%
	19	49523	7.5%	0.0%	92.5%	22.0%	5.2%	72.8%	14.44%
	20	40346	21.6%	0.0%	78.4%	32.8%	0.0%	67.2%	11.20%
	21	31439	2.3%	23.3%	74.4%	41.5%	0.0%	58.5%	39.24%
	22	23441	12.2%	8.8%	79.0%	45.5%	1.4%	53.1%	33.30%
	23	35596	21.0%	5.1%	73.9%	29.6%	0.0%	70.4%	8.64%
	24	75215	26.3%	8.8%	64.9%	47.0%	0.3%	52.8%	20.63%
	25	39519	30.1%	0.0%	69.9%	29.0%	2.5%	68.5%	-1.05%
	26	24515	4.1%	6.6%	89.3%	16.9%	0.9%	82.1%	12.82%
	27	53968	17.3%	0.0%	82.7%	22.5%	0.0%	77.5%	5.14%
	28	37542	14.0%	3.9%	82.1%	16.1%	11.0%	72.9%	2.06%
	29	48489	41.0%	6.0%	53.0%	6.4%	2.7%	90.9%	-34.59%
	30	79946	22.0%	0.0%	78.0%	10.7%	20.7%	68.6%	-11.35%
Protection zone	31	45411	53.5%	0.0%	46.5%	9.7%	32.5%	57.8%	-43.78%
	32	17710	49.5%	0.0%	50.5%	24.0%	1.6%	74.4%	-25.49%
	33	96585	37.5%	3.0%	59.5%	44.4%	2.8%	52.8%	6.94%
	34	57252	19.7%	0.0%	80.3%	31.0%	0.1%	68.8%	11.32%
	35	24043	16.1%	0.0%	83.9%	14.8%	3.3%	81.9%	-1.28%
	36	33817	20.3%	0.0%	79.7%	44.5%	0.0%	55.5%	24.12%
	37	23715	8.3%	0.0%	91.7%	13.6%	0.0%	86.4%	5.30%
	38	26995	14.8%	0.0%	85.2%	33.0%	0.0%	67.0%	18.22%
	39	75070	26.3%	0.0%	73.7%	11.8%	10.8%	77.4%	-14.48%
	40	52325	22.6%	0.0%	77.4%	29.6%	1.2%	69.2%	6.94%
	41	30613	15.8%	0.0%	84.2%	11.1%	1.2%	87.7%	-4.70%
	42	19694	16.1%	0.0%	83.9%	22.8%	1.9%	75.4%	6.63%
	43	83999	38.2%	0.0%	61.8%	29.1%	1.3%	69.5%	-9.03%
	44	30667	20.1%	0.0%	79.9%	35.5%	0.0%	64.5%	15.41%
	45	26945	6.4%	22.7%	70.9%	22.3%	0.6%	77.0%	15.94%
	46	27960	18.4%	0.5%	81.1%	14.2%	0.0%	85.8%	-4.13%
	47	43221	36.1%	1.4%	62.5%	37.8%	0.3%	61.9%	1.68%
	48	41266	34.8%	0.0%	65.2%	50.8%	0.0%	49.2%	16.04%
	49	23242	35.4%	0.0%	64.6%	28.2%	0.0%	71.8%	-7.29%
	50	44144	14.4%	1.3%	84.3%	29.9%	0.0%	70.1%	15.49%

Table 22 (Continued)

	ID	Shrimp farm area (m^2)	2011 (%)			2019 (%)			Mangrove change (%)
			Mangrove	Propagule	Other	Mangrove	Propagule	Other	
Protection zone	51	73670	28.3%	0.9%	70.8%	37.6%	0.0%	62.4%	9.32%
	52	22969	27.6%	5.4%	67.0%	45.0%	0.0%	55.0%	17.43%
	53	26578	16.6%	17.4%	66.0%	8.9%	0.0%	91.1%	-7.69%
	54	19724	25.1%	0.0%	74.9%	18.6%	0.0%	81.4%	-6.55%
	55	23921	17.5%	0.0%	82.5%	30.6%	0.0%	69.4%	13.10%
	56	46501	2.5%	0.0%	97.5%	16.3%	9.0%	74.7%	13.77%
	57	36015	0.0%	0.0%	100.0%	20.1%	0.0%	79.9%	20.13%
	58	59054	30.4%	0.0%	69.6%	26.0%	0.7%	73.3%	-4.41%
	59	116962	19.4%	2.0%	78.6%	36.6%	0.0%	63.4%	17.19%
	60	52796	27.1%	0.0%	72.9%	19.5%	17.7%	62.8%	-7.63%

APPENDIX J – Statistics tests outcomes image analysis

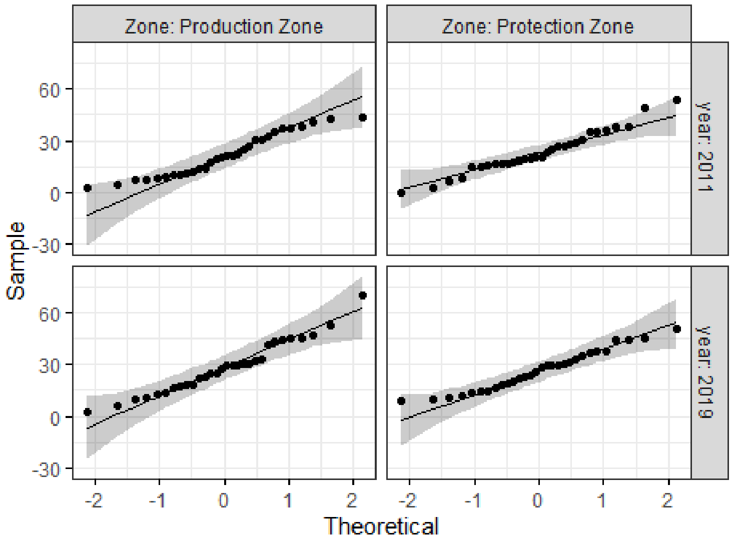


Figure 50 Quantile Quantile plots for manually delineated mangrove cover 2011, 2019 in the production and protection zone

```
# A tibble: 4 x 5
  Zone            year  variable statistic      p
  <fct>           <fct> <chr>        <dbl>  <dbl>
1 Production Zone 2011  Area         0.940 0.0925
2 Production Zone 2019  Area         0.964 0.391
3 Protection Zone 2011  Area         0.969 0.512
4 Protection Zone 2019  Area         0.964 0.381
```

Figure 51 Shapiro-Wilk test outcomes for manually delineated mangrove cover 2011, 2019 in the production and protection zone

```
# A tibble: 1 x 6
  Zone            year  SF_ID  Area is.outlier is.extreme
  <fct>           <fct> <fct> <dbl> <lgl>      <lgl>
1 Protection Zone 2011  31     53.5 TRUE       FALSE
```

Figure 52 Outlier of manual delineated mangrove cover for 2011, 2019 in the production and protection zone

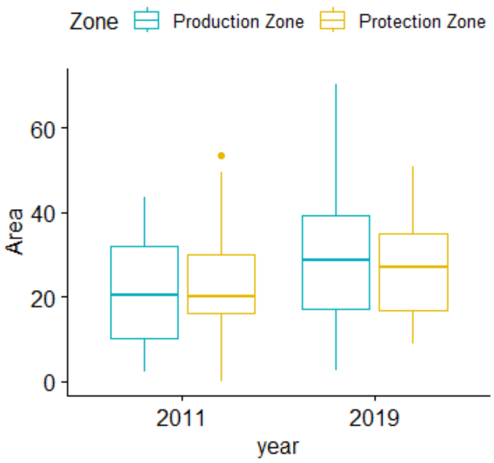


Figure 53 Boxplot including outlier of manually delineated mangrove cover for 2011, 2019 in the production and protection zone

```
>
> #Homogeneity of variances ----
> data %>%
+     group_by(year) %>%
+     levene_test(Area ~ Zone)
# A tibble: 2 x 5
  year    df1   df2 statistic     p
  <fct> <int> <int>     <dbl> <dbl>
1 2011      1    58     0.258 0.614
2 2019      1    58     1.21  0.276
```

Figure 54 Homogeneity of variance as assessed by Levene's test of manually delineated mangrove cover for 2011, 2019 in the production and protection zone

```
> #Homogeneity of covariances assumption ----
>  box_m(data[, "Area", drop = FALSE], data$Zone)
# A tibble: 1 x 4
  statistic p.value parameter method
      <dbl>   <dbl>     <dbl> <chr>
1      1.69   0.193         1 Box's M-test for Homogeneity of Covariance Matrices
>  box_m(data[, "Area", drop = FALSE], data$year)
# A tibble: 1 x 4
  statistic p.value parameter method
      <dbl>   <dbl>     <dbl> <chr>
1     0.441   0.507         1 Box's M-test for Homogeneity of Covariance Matrices
>
```

Figure 55 Homogeneity of covariances as assessed by Box's M-test of manually delineated mangrove cover for 2011, 2019 in the production and protection zone

```
> #Two-way mixed ANOVA test: ----
>  res.aov <- anova_test(
+    data = data, dv = Area, wid = SF_ID,
+    between = Zone, within = year
+  )
>  get_anova_table(res.aov)
ANOVA Table (type II tests)

     Effect DFn DFd        F     p p<.05      ges
1      Zone   1  58 0.000132 0.991       1.32e-06
2      year   1  58 5.261000 0.025     * 3.70e-02
3 Zone:year   1  58 0.632000 0.430       5.00e-03
>  summary(res.aov)
    Effect               DFn          DFd           F                    p               p<.05
 Length:3           Min.   :1   Min.   :58   Min.   :0.000132   Min.   :0.0250   Length:3
 Class :character   1st Qu.:1   1st Qu.:58   1st Qu.:0.316066   1st Qu.:0.2275   Class :character
 Mode  :character   Median :1   Median :58   Median :0.632000   Median :0.4300   Mode  :character
                    Mean   :1   Mean   :58   Mean   :1.964377   Mean   :0.4820
                    3rd Qu.:1   3rd Qu.:58   3rd Qu.:2.946500   3rd Qu.:0.7105
                    Max.   :1   Max.   :58   Max.   :5.261000   Max.   :0.9910
      ges
 Min.   :1.320e-06
 1st Qu.:2.501e-03
 Median :5.000e-03
 Mean   :1.400e-02
 3rd Qu.:2.100e-02
 Max.   :3.700e-02
```

Figure 56 Two-way mixed ANOVA test outcome of manually delineated mangrove cover for 2011, 2019 in the production and protection zone

```
>  #Post HOC----
>   data %>%
+    pairwise_t_test(
+      Area ~ year, paired = TRUE,
+      p.adjust.method = "bonferroni"
+    )
# A tibble: 1 x 10
  .y.   group1 group2    n1    n2 statistic    df     p p.adj p.adj.signif
* <chr> <chr>  <chr>  <int> <int>     <dbl> <dbl> <dbl> <dbl> <chr>
1 Area  2011   2019      60    60     -2.30    59 0.025 0.025 *
>
>  data %>%
+    pairwise_t_test(
+      Area ~ Zone,
+      p.adjust.method = "bonferroni"
+    )
# A tibble: 1 x 9
  .y.   group1          group2             n1    n2     p p.signif p.adj p.adj.signif
* <chr> <chr>           <chr>           <int> <int> <dbl> <chr>    <dbl> <chr>
1 Area  Production Zone Protection Zone    60    60  0.99 ns        0.99 ns
>
```

Figure 57 Post-hoc testing using Bonferroni adjusted p-value (main effects) of manually delineated mangrove cover for 2011, 2019 in the production and protection zone

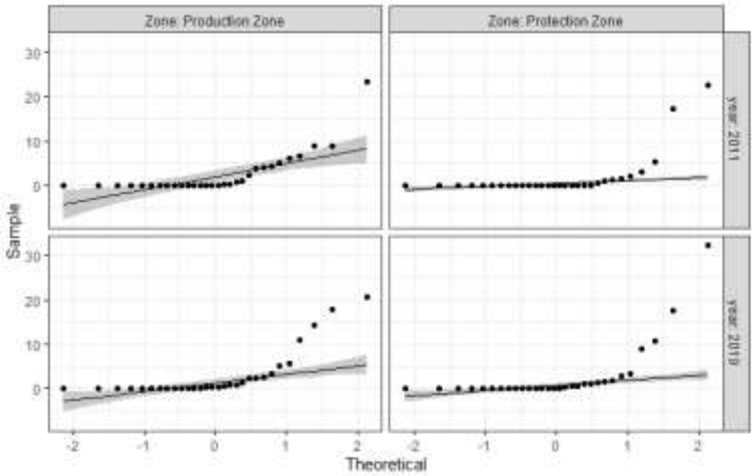


Figure 58 Quantile Quantile plots for manually delineated propagule cover 2011, 2019 in the production and protection zone

```
> #Shapiro Wilk
>  data %>%
+    group_by(Zone, year) %>%
+    shapiro_test(Area)
# A tibble: 4 x 5
  Zone            year  variable statistic        p
  <fct>           <fct> <chr>        <dbl>    <dbl>
1 Production Zone 2011  Area         0.585 4.85e- 8
2 Production Zone 2019  Area         0.609 9.32e- 8
3 Protection Zone 2011  Area         0.407 6.35e-10
4 Protection Zone 2019  Area         0.478 3.16e- 9
```

Figure 59 Shapiro-Wilk test outcomes for manually delineated propagule cover 2011, 2019 in the production and protection zone

```
> data %>%
+   group_by(Zone, year) %>%
+   identify_outliers(Area)
# A tibble: 13 x 6
   Zone            year  SF_ID  Area is.outlier is.extreme
   <fct>           <fct> <fct> <dbl> <lgl>      <lgl>
 1 Production Zone 2011  21    23.3  TRUE       TRUE
 2 Production Zone 2019  3     14.4  TRUE       TRUE
 3 Production Zone 2019  6     17.8  TRUE       TRUE
 4 Production Zone 2019  28    11.0  TRUE       TRUE
 5 Production Zone 2019  30    20.7  TRUE       TRUE
 6 Protection Zone 2011  33     3.04 TRUE       FALSE
 7 Protection Zone 2011  45    22.7  TRUE       TRUE
 8 Protection Zone 2011  52     5.36 TRUE       TRUE
 9 Protection Zone 2011  53    17.4  TRUE       TRUE
10 Protection Zone 2019  31    32.5  TRUE       TRUE
11 Protection Zone 2019  39    10.8  TRUE       TRUE
12 Protection Zone 2019  56     9.02 TRUE       TRUE
13 Protection Zone 2019  60    17.7  TRUE       TRUE
```

Figure 60: Outliers of manual delineated propagule cover for 2011, 2019 in the production and protection zone

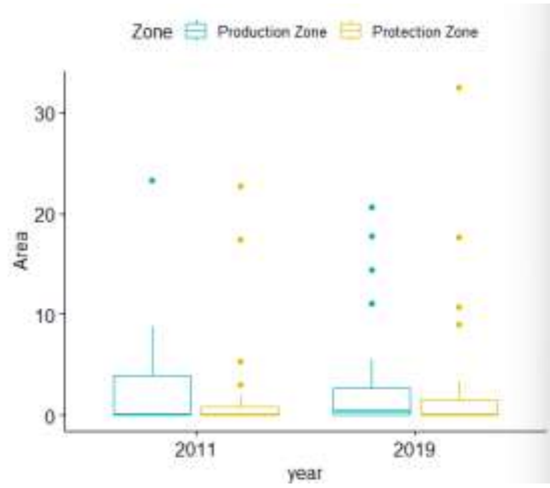


Figure 61 Boxplot including outlier of manually delineated propagule cover for 2011, 2019 in the production and protection zone

```
> #Homogeneity of variances ----
> data %>%
+    group_by(year) %>%
+    levene_test(Area ~ Zone)
# A tibble: 2 x 5
  year    df1   df2 statistic     p
  <fct> <int> <int>     <dbl> <dbl>
1 2011      1    58   0.291   0.592
2 2019      1    58   0.00706 0.933
```

Figure 62 Homogeneity of variance as assessed by Levene's test of manually delineated propagule cover for 2011, 2019 in the production and protection zone

```
> #Homogeneity of covariances assumption ----
>  box_m(data[, "Area", drop = FALSE], data$Zone)
# A tibble: 1 × 4
  statistic p.value parameter method
      <dbl>   <dbl>     <dbl> <chr>
1      1.38   0.240         1 Box's M-test for Homogeneity of Covariance Matrices
>  box_m(data[, "Area", drop = FALSE], data$year)
# A tibble: 1 × 4
  statistic p.value parameter method
      <dbl>   <dbl>     <dbl> <chr>
1      2.85  0.0911         1 Box's M-test for Homogeneity of Covariance Matrices
```

Figure 63 Homogeneity of covariances as assessed by Box's M-test of manually delineated propagule cover for 2011, 2019 in the production and protection zone

```
> #Two-way mixed ANOVA test: ----
>  res.aov <- anova_test(
+    data = data, dv = Area, wid = SF_ID,
+    between = Zone, within = year
+  )
>  get_anova_table(res.aov)
ANOVA Table (type II tests)

     Effect DFn DFd     F     p p<.05      ges
1      Zone   1  58 0.213 0.646       0.002000
2      year   1  58 0.468 0.497       0.005000
3 Zone:year   1  58 0.054 0.818       0.000532
>  summary(res.aov)
    Effect               DFn          DFd            F                p
 Length:3           Min.   :1   Min.   :58   Min.   :0.0540   Min.   :0.4970
 Class :character   1st Qu.:1   1st Qu.:58   1st Qu.:0.1335   1st Qu.:0.5715
 Mode  :character   Median :1   Median :58   Median :0.2130   Median :0.6460
                    Mean   :1   Mean   :58   Mean   :0.2450   Mean   :0.6537
                    3rd Qu.:1   3rd Qu.:58   3rd Qu.:0.3405   3rd Qu.:0.7320
                    Max.   :1   Max.   :58   Max.   :0.4680   Max.   :0.8180
    p<.05               ges
 Length:3           Min.   :0.000532
 Class :character   1st Qu.:0.001266
 Mode  :character   Median :0.002000
                    Mean   :0.002511
                    3rd Qu.:0.003500
                    Max.   :0.005000
```

Figure 64 Two-way mixed ANOVA test outcome of manually delineated propagule cover for 2011, 2019 in the production and protection zone

```
> #Post HOC----
>   data %>%
+    pairwise_t_test(
+      Area ~ year, paired = TRUE,
+      p.adjust.method = "bonferroni"
+    )
# A tibble: 1 × 10
  .y.   group1 group2    n1    n2 statistic    df     p p.adj p.adj.signif
* <chr> <chr>  <chr>  <int> <int>     <dbl> <dbl> <dbl> <dbl> <chr>
1 Area  2011   2019      60    60    -0.689    59 0.493 0.493 ns
>
>  data %>%
+    pairwise_t_test(
+      Area ~ Zone,
+      p.adjust.method = "bonferroni"
+    )
# A tibble: 1 × 9
  .y.   group1          group2             n1    n2     p p.signif p.adj p.adj._'
* <chr> <chr>           <chr>           <int> <int> <dbl> <chr>    <dbl> <chr>
1 Area  Production Zone Protection Zone    60    60  0.67 ns        0.67 ns
# … with abbreviated variable name 'p.adj.signif
```

Figure 65 Post-hoc testing using Bonferroni adjusted p-value (main effects) of manually delineated propagule cover for 2011, 2019 in the production and protection zone

APPENDIX K – Mangrove coverages analysis: statistical results

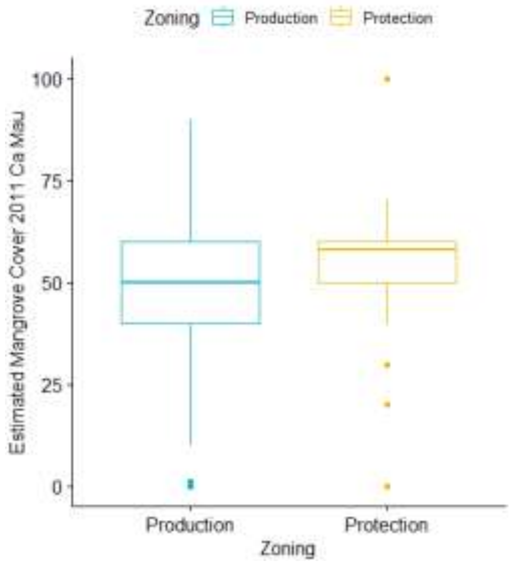


Figure 66 Boxplot with outliers estimated mangrove cover 2011 Ca Mau

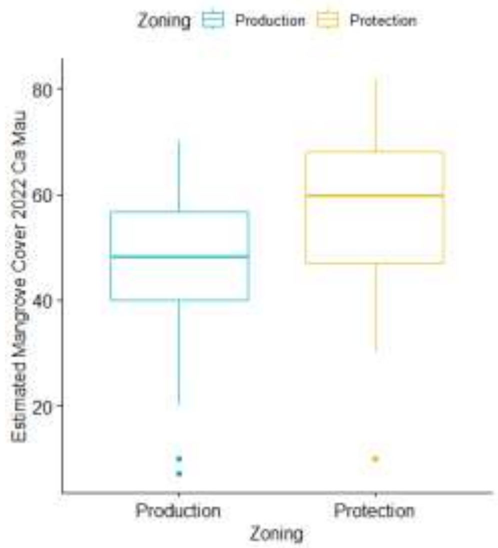


Figure 67 Boxplot with outliers estimated mangrove cover 2022 Ca Mau

	Zoning	Year	count	min	mean	max	sd
	<fct>	<fct>	<int>	<dbl>	<dbl>	<dbl>	<dbl>
1	Production	2011	105	0	48.9	90	16.0
2	Production	2022	92	7.14	46.6	70	13.0
3	Protection	2011	43	0	53.7	100	16.5
4	Protection	2022	46	10	54.8	81.8	15.7

Figure 68 General statistics estimated mangrove cover Ca Mau

```
# A tibble: 8 × 7
  Year  Zoning     Disct      perc_MOF NEAR_DIST is.ou…¹ is.ex…²
  <fct> <fct>      <fct>         <dbl>     <dbl> <lgl>   <lgl>
1 2011  Production Dam Doi        1       11895. TRUE    FALSE
2 2011  Production Ngoc Hien     90        8952. TRUE    FALSE
3 2011  Production Ngoc Hien      0        9090. TRUE    FALSE
4 2011  Production Nam Can       10        9404. TRUE    FALSE
5 2011  Protection Phu Tan        0         448. TRUE    FALSE
6 2011  Protection Phu Tan      100         292. TRUE    FALSE
7 2011  Protection Phu Tan        0        3522. TRUE    FALSE
8 2022  Production Nam Can        7.14     5704. TRUE    FALSE
# … with abbreviated variable names ¹is.outlier, ²is.extreme
```

Figure 69 Outliers t-T 2011 vs 2022 estimated mangrove cover Ca Mau

```
  Year  variable statistic           p
  <fct> <chr>        <dbl>       <dbl>
1 2011  perc_MOF     0.913 0.0000000970
2 2022  perc_MOF     0.967 0.00187
```

Figure 70 Shapiro-Wilk test t-T 2011 vs 2022 estimated mangrove cover Ca Mau including outliers (n=286)

```
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022     148   138     11154 0.175
> SDData %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022    0.0802   148   138 small
```

Figure 71 Wilcoxon test t-T 2011 vs 2022 estimated mangrove cover Ca Mau including outliers (n=286)

```
  Year  variable statistic          p
  <fct> <chr>        <dbl>      <dbl>
1 2011  perc_MOF     0.923 0.000000690
2 2022  perc_MOF     0.977 0.0207
```

Figure 72 Shapiro-Wilk test t-T 2011 vs 2022 estimated mangrove cover Ca Mau excluding outliers (n=275)

```
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022     141   134    10312. 0.187
> SDData %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022    0.0797   141   134 small
```

Figure 73 Wilcoxon test t-T 2011 vs 2022 estimated mangrove cover Ca Mau excluding outliers (n=275)

```
# A tibble: 7 × 7
  Zoning     Year  Disct     perc_MOF NEAR_DIST is.outlier is.extreme
  <fct>      <fct> <fct>        <dbl>     <dbl> <lgl>      <lgl>
1 Production 2011  Dam Doi          1    11895. TRUE       FALSE
2 Production 2011  Ngoc Hien        0     9090. TRUE       FALSE
3 Protection 2011  Phu Tan          0      448. TRUE       TRUE
4 Protection 2011  Ngoc Hien       20     2031. TRUE       FALSE
5 Protection 2011  Phu Tan        100      292. TRUE       TRUE
6 Protection 2011  Phu Tan          0     3522. TRUE       TRUE
7 Protection 2011  Nam Can         30     1857. TRUE       FALSE
```

Figure 74 Outliers a-b 2011 estimated mangrove cover Ca Mau

```
  Zoning     variable statistic          p
  <fct>      <chr>        <dbl>      <dbl>
1 Production perc_MOF     0.948 0.000465
2 Protection perc_MOF     0.763 0.000000625
>
```

Figure 75 Shapiro-Wilk test a-b 2011 estimated mangrove cover Ca Mau including outliers (n=148)

```
>       # Not normal distribution thus non-parametric Wilcox test
>       SDData11 %>% wilcox_test(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statistic      p
* <chr>    <chr>      <chr>      <int> <int>     <dbl>  <dbl>
1 perc_MOF Production Protection   105    43      1766 0.0361
>       SDData11 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnitude
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection   0.172   105    43 small
>
```

Figure 76 Wilcoxon test outcome a-b 2011 including outliers (n=148)

```
# A tibble: 2 × 4
  Zoning     variable statistic         p
  <fct>      <chr>        <dbl>     <dbl>
1 Production perc_MOF     0.945 0.000392
2 Protection perc_MOF     0.820 0.0000183
```

Figure 77 Shapiro-Wilk test a-b 2011 estimated mangrove cover Ca Mau excluding outliers (n=141)

```
>       SDData11 %>% wilcox_test(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statistic     p
* <chr>    <chr>      <chr>      <int> <int>     <dbl> <dbl>
1 perc_MOF Production Protection   101    40      1517  0.02
>       SDData11 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnitude
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection   0.196   101    40 small
```

Figure 78 Wilcoxon test outcome a-b 2011 excluding outliers (n=141)

```
  Zoning     Year  Disct      perc_MOF NEAR_DIST is.outlier is.extreme
  <fct>      <fct> <fct>         <dbl>     <dbl> <lgl>      <lgl>
1 Production 2022  Ngoc Hien     10        4662. TRUE       FALSE
2 Production 2022  Nam Can        7.14     5704. TRUE       FALSE
3 Protection 2022  Phu Tan       10        1350. TRUE       FALSE
4 Protection 2022  Phu Tan       10        1374. TRUE       FALSE
>
```

Figure 79 Outliers A-B 2022 estimated mangrove cover Ca Mau

```
# A tibble: 2 × 4
  Zoning     variable statistic       p
  <fct>      <chr>        <dbl>   <dbl>
1 Production perc_MOF     0.966 0.0170
2 Protection perc_MOF     0.917 0.00304
```

Figure 80 Shapiro-Wilks test A-B including outliers (n=138)

```
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 stati…¹       p
* <chr>    <chr>      <chr>      <int> <int>   <dbl>   <dbl>
1 perc_MOF Production Protection    92    46    1343 4.6e-4
# … with abbreviated variable name ¹statistic
>       SDData22 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magni…¹
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protecti…    0.298    92    46 small
```

Figure 81 Wilcoxon test outcome A-B 2022 including outliers (n=138)

```
  Zoning     variable statistic      p
  <fct>      <chr>        <dbl>  <dbl>
1 Production perc_MOF     0.973 0.0534
2 Protection perc_MOF     0.951 0.0607
```

Figure 82 Shapiro-Wilk test A-B 2022 estimated mangrove cover Ca Mau excluding outliers (n=134)

```
>       SDData22 %>% wilcox_test(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statis…¹     p
* <chr>    <chr>      <chr>      <int> <int>    <dbl> <dbl>
1 perc_MOF Production Protection    90    44     1162  1e-4
# … with abbreviated variable name ¹statistic
>       SDData22 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magni…¹
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protecti…    0.336    90    44 modera…
```

Figure 83 Wilcoxon test A-B outcome 2022 excluding outliers (n=134)

```
  Zoning     Year  Disct      perc_MOF NEAR_DIST is.outlier is.extreme
  <fct>      <fct> <fct>         <dbl>     <dbl> <lgl>      <lgl>
1 Production 2011  Dam Doi        1       11895. TRUE       FALSE
2 Production 2011  Ngoc Hien      0        9090. TRUE       FALSE
3 Production 2022  Nam Can        7.14     5704. TRUE       FALSE
```

Figure 84 Outliers a-A production zone estimated mangrove cover Ca Mau

```
# A tibble: 1 × 4
  Zoning     variable statistic         p
  <fct>      <chr>        <dbl>     <dbl>
1 Production perc_MOF     0.964 0.0000581
```

Figure 85 Shapiro-Wilk test a-A production zone estimated mangrove cover Ca Mau including outliers (n=197)

```
>   SDDatapd %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic      p
* <chr>    <chr>  <chr>  <int> <int>     <dbl>  <dbl>
1 perc_MOF 2011   2022     105    92      5571 0.0621
>       SDDatapd %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.133   105    92 small
```

Figure 86 Wilcoxon test a-A production zone estimated mangrove cover Ca Mau outcome including outliers (n=197)

```
  Zoning     variable statistic        p
  <fct>      <chr>        <dbl>    <dbl>
1 Production perc_MOF     0.966 0.000125
```

Figure 87 Shapiro-Wilk test a-A production zone estimated mangrove cover Ca Mau excluding outliers (n=191)

```
>       SDDatapd %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic      p
* <chr>    <chr>  <chr>  <int> <int>     <dbl>  <dbl>
1 perc_MOF 2011   2022     101    90     5276.  0.0541
>       SDDatapd %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.139   101    90 small
```

Figure 88 Wilcoxon test a-A production zone estimated mangrove cover Ca Mau outcome excluding outliers (n=191)

```
# A tibble: 11 × 7
   Zoning     Year  Disct     perc_MOF NEAR_DIST is.outlier is.extreme
   <fct>      <fct> <fct>        <dbl>     <dbl> <lgl>      <lgl>
 1 Protection 2011  Phu Tan        0        448. TRUE       TRUE
 2 Protection 2011  Ngoc Hien     20       2031. TRUE       FALSE
 3 Protection 2011  Phu Tan      100        292. TRUE       TRUE
 4 Protection 2011  Phu Tan        0       3522. TRUE       TRUE
 5 Protection 2011  Nam Can       30       1857. TRUE       FALSE
 6 Protection 2022  Dam Doi       81.8     1496. TRUE       FALSE
 7 Protection 2022  Ngoc Hien     30       3071. TRUE       FALSE
 8 Protection 2022  Phu Tan       30       1160. TRUE       FALSE
 9 Protection 2022  Phu Tan       10       1350. TRUE       TRUE
10 Protection 2022  Ngoc Hien     33.3     3587. TRUE       FALSE
11 Protection 2022  Phu Tan       10       1374. TRUE       TRUE
```

Figure 89 Outliers b-B protection zone estimated mangrove cover Ca Mau

```
  Zoning     variable statistic           p
  <fct>      <chr>        <dbl>       <dbl>
1 Protection perc_MOF     0.876 0.000000450
```

Figure 90 Shapiro-Wilk test b-B protection zone estimated mangrove cover Ca Mau including outliers (n=89)

```
>       SDDatapt %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022      43    46       931 0.633
>       SDDatapt %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022    0.0511    43    46 small
```

Figure 91 Wilcoxon test b-B protection zone estimated mangrove cover Ca Mau including outliers (n=89)

```
  Zoning     variable statistic        p
  <fct>      <chr>        <dbl>    <dbl>
1 Protection perc_MOF     0.933 0.000517
```

Figure 92 Shapiro-Wilk test b-B protection zone estimated mangrove cover Ca Mau excluding outliers (n=77)

```
>       SDDatapt %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022      38    39       690   0.6
>       SDDatapt %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
```

Figure 93 Wilcoxon test b-B protection zone estimated mangrove cover Ca Mau excluding outliers (n=77)

```
# A tibble: 9 x 7
  Year  Zoning     Disct   perc_MOF NEAR_DIST is.outlier is.extreme
  <fct> <fct>      <fct>      <dbl>     <dbl> <lgl>      <lgl>
1 2011  Production Nam Can    30        13893. TRUE       FALSE
2 2011  Production Nam Can    30        11195. TRUE       FALSE
3 2011  Production Nam Can    10         9404. TRUE       TRUE
4 2011  Production Nam Can    30         9873. TRUE       FALSE
5 2011  Production Nam Can    24         3961. TRUE       FALSE
6 2011  Production Nam Can    25         4801. TRUE       FALSE
7 2011  Production Nam Can    30         4354. TRUE       FALSE
8 2011  Protection Nam Can    30         1857. TRUE       FALSE
9 2022  Production Nam Can     7.14      5704. TRUE       TRUE
```

Figure 94 Outliers d-D estimated mangrove cover Nam Can

```
  Year  variable statistic          p
  <fct> <chr>        <dbl>      <dbl>
1 2011  perc_MOF     0.876 0.00000333
2 2022  perc_MOF     0.822 0.000263
```

Figure 95 Shapiro-Wilk test d-D estimated mangrove cover Nam Can including outliers (n=101)

```
>       SDDatanc %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 x 7
  .y.      group1 group2    n1    n2 statistic      p
* <chr>    <chr>  <chr>  <int> <int>     <dbl>  <dbl>
1 perc_MOF 2011   2022      73    28       776 0.0609
>       SDDatanc %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 x 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.187    73    28 small
```

Figure 96 Wilcoxon test d-D estimated mangrove cover Nam Can including outliers (n=101)

```
  Year  variable statistic        p
  <fct> <chr>        <dbl>    <dbl>
1 2011  perc_MOF     0.911 0.000182
2 2022  perc_MOF     0.891 0.00823
```

Figure 97 Shapiro-Wilk test d-D estimated mangrove cover Nam Can excluding outliers (n=92)

```
>       SDDatanc %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022      65    27       703 0.133
>       SDDatanc %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.157    65    27 small
```

Figure 98 Wilcoxon test d-D estimated mangrove cover Nam Can excluding outliers (n=92)

```
   Zoning     Year  Disct    perc_MOF NEAR_DIST is.outlier is.extreme
   <fct>      <fct> <fct>       <dbl>     <dbl> <lgl>      <lgl>
 1 Production 2011  Nam Can        30    13893. TRUE       FALSE
 2 Production 2011  Nam Can        30    11195. TRUE       FALSE
 3 Production 2011  Nam Can        10     9404. TRUE       TRUE
 4 Production 2011  Nam Can        30     9873. TRUE       FALSE
 5 Production 2011  Nam Can        24     3961. TRUE       FALSE
 6 Production 2011  Nam Can        25     4801. TRUE       FALSE
 7 Production 2011  Nam Can        30     4354. TRUE       FALSE
 8 Protection 2011  Nam Can        70     3735. TRUE       FALSE
 9 Protection 2011  Nam Can        30     1857. TRUE       FALSE
10 Protection 2011  Nam Can        70     1042. TRUE       FALSE
```

Figure 99 Outliers aD-bD 2011 estimated mangrove cover Nam Can

```
  Zoning     variable statistic        p
  <fct>      <chr>        <dbl>    <dbl>
1 Production perc_MOF     0.889 0.000161
2 Protection perc_MOF     0.878 0.0131
```

Figure 100 Shapiro-Wilk aD-bD 2011 estimated mangrove cover Nam Can including outliers (n=73)

```
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statistic     p
* <chr>    <chr>      <chr>      <int> <int>     <dbl> <dbl>
1 perc_MOF Production Protection    52    21       447 0.227
>       SDDatanc11 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnitude
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection   0.142    52    21 small
```

Figure 101 Wilcoxon test aD-bD 2011 estimated mangrove cover Nam Can including outliers (n=73)

```
  Zoning     variable statistic       p
  <fct>      <chr>        <dbl>   <dbl>
1 Production perc_MOF     0.911 0.00210
2 Protection perc_MOF     0.879 0.0171
```

Figure 102 Shapiro-Wilk aD-bD 2011 estimated mangrove cover Nam Can excluding outliers (n=65)

```
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statistic     p
* <chr>    <chr>      <chr>      <int> <int>     <dbl> <dbl>
1 perc_MOF Production Protection    45    20       400 0.477
>       SDDatanc11 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnitude
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection  0.0890    45    20 small
```

Figure 103 Wilcoxon test aD-bD 2011 estimated mangrove cover Nam Can excluding outliers (n=65)

```
# A tibble: 1 × 7
  Zoning     Year  Disct    perc_MOF NEAR_DIST is.outlier is.extreme
  <fct>      <fct> <fct>       <dbl>     <dbl> <lgl>      <lgl>
1 Protection 2022  Nam Can      43.8     2164. TRUE       FALSE
```

Figure 104 Outlier AD-BD 2022 estimated mangrove cover Nam Can

```
  Zoning     variable statistic      p
  <fct>      <chr>        <dbl>  <dbl>
1 Production perc_MOF     0.889 0.114
2 Protection perc_MOF     0.864 0.0217
```

Figure 105 Shapiro-Wilk AD-BD 2022 estimated mangrove cover Nam Can including outlier (n=28)

```
>       SDDatanc22 %>% wilcox_test(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statis…¹       p
* <chr>    <chr>      <chr>      <int> <int>    <dbl>   <dbl>
1 perc_MOF Production Protection    12    16       39 0.00762
# … with abbreviated variable name ¹statistic
>       SDDatanc22 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnit…¹
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection   0.509    12    16 large
# … with abbreviated variable name ¹magnitude
```

Figure 106 Wilcoxon test AD-BD 2022 estimated mangrove cover Nam Can including outlier (n=28)

```
  Zoning     variable statistic      p
  <fct>      <chr>        <dbl>  <dbl>
1 Production perc_MOF     0.920 0.320
2 Protection perc_MOF     0.864 0.0217
```

Figure 107 Shapiro test AD-BD 2022 estimated mangrove cover Nam Can excluding outlier (n=27)

```
# A tibble: 1 × 7
  .y.      group1     group2        n1    n2 statistic      p
* <chr>    <chr>      <chr>      <int> <int>     <dbl>  <dbl>
1 perc_MOF Production Protection    11    16        39 0.0147
>       SDDatanc22 %>% wilcox_effsize(perc_MOF ~ Zoning)
# A tibble: 1 × 7
  .y.      group1     group2     effsize    n1    n2 magnit…¹
* <chr>    <chr>      <chr>        <dbl> <int> <int> <ord>
1 perc_MOF Production Protection   0.474    11    16 moderate
```

Figure 108 Wilcoxon test AD-BD 2022 estimated mangrove cover Nam Can excluding outlier (n=27)

```
# A tibble: 7 × 7
  Year  Zoning     Disct   perc_MOF NEAR_DIST is.outlier is.extreme
  <fct> <fct>      <fct>      <dbl>     <dbl> <lgl>      <lgl>
1 2011  Production Nam Can       30    13893. TRUE       FALSE
2 2011  Production Nam Can       30    11195. TRUE       FALSE
3 2011  Production Nam Can       10     9404. TRUE       TRUE
4 2011  Production Nam Can       30     9873. TRUE       FALSE
5 2011  Production Nam Can       24     3961. TRUE       FALSE
6 2011  Production Nam Can       25     4801. TRUE       FALSE
7 2011  Production Nam Can       30     4354. TRUE       FALSE
```

Figure 109 Outliers aD-AD production zone estimated mangrove cover Nam Can

```
  Year  variable statistic        p
  <fct> <chr>        <dbl>    <dbl>
1 2011  perc_MOF     0.889 0.000163
2 2022  perc_MOF     0.889 0.114
```

Figure 110 Shapiro-Wilk test aD-AD production zone estimated mangrove cover Nam Can including outliers (n=64)

```
>       SDDatancpd %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022      52    12       366 0.354
>       SDDatancpd %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.117    52    12 small
```

Figure 111 Wilcoxon test aD-AD production zone estimated mangrove cover Nam Can including outliers (n=64)

```
  Year  variable statistic       p
  <fct> <chr>        <dbl>   <dbl>
1 2011  perc_MOF     0.911 0.00210
2 2022  perc_MOF     0.920 0.320
```

Figure 112 Shapiro-Wilk test aD-AD production zone estimated mangrove cover Nam Can excluding outliers (n=56)

```
>       SDDatancpd %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic     p
* <chr>    <chr>  <chr>  <int> <int>     <dbl> <dbl>
1 perc_MOF 2011   2022      45    11       314  0.17
>       SDDatancpd %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.185    45    11 small
```

Figure 113 Wilcoxon test aD-AD production zone estimated mangrove cover Nam Can excluding outliers (n=56)

```
# A tibble: 4 × 7
  Year  Zoning     Disct   perc_MOF NEAR_DIST is.outlier is.extreme
  <fct> <fct>      <fct>      <dbl>     <dbl> <lgl>      <lgl>
1 2011  Protection Nam Can     70       3735. TRUE       FALSE
2 2011  Protection Nam Can     30       1857. TRUE       FALSE
3 2011  Protection Nam Can     70       1042. TRUE       FALSE
4 2022  Protection Nam Can     43.8     2164. TRUE       FALSE
```

Figure 114 Outliers bD-BD protection zone estimated mangrove cover Nam Can

```
  Year  variable statistic      p
  <fct> <chr>        <dbl>  <dbl>
1 2011  perc_MOF     0.878 0.0133
2 2022  perc_MOF     0.864 0.0217
```

Figure 115 Shapiro test bD-BD protection zone estimated mangrove cover Nam Can including outliers (n=37)

```
>       SDDatancpt %>% wilcox_test(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic       p
* <chr>    <chr>  <chr>  <int> <int>     <dbl>   <dbl>
1 perc_MOF 2011   2022      21    16        72 0.00312
>       SDDatancpt %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.488    21    16 moderate
```

Figure 116 Wilcoxon test bD-BD protection zone estimated mangrove cover Nam Can including outliers (n=37)

```
  Year  variable statistic      p
  <fct> <chr>        <dbl>  <dbl>
1 2011  perc_MOF     0.879 0.0171
2 2022  perc_MOF     0.864 0.0217
```

Figure 117 Shapiro-Wilk test bD-BD protection zone estimated mangrove cover Nam Can excluding outliers (n=36)

```
# A tibble: 1 × 7
  .y.      group1 group2    n1    n2 statistic       p
* <chr>    <chr>  <chr>  <int> <int>     <dbl>   <dbl>
1 perc_MOF 2011   2022      20    16        72 0.00489
>       SDDatancpt %>% wilcox_effsize(perc_MOF ~ Year)
# A tibble: 1 × 7
  .y.      group1 group2 effsize    n1    n2 magnitude
* <chr>    <chr>  <chr>    <dbl> <int> <int> <ord>
1 perc_MOF 2011   2022     0.472    20    16 moderate
```

Figure 118 Wilcoxon test bD-BD protection zone estimated mangrove cover Nam Can excluding outliers (n=36)

Remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm Nam Can

```
+      identify_outliers(PERC11)
[1] Zone        Method      SF_ID       Area        PERC11
[6] NEAR_DIST   is.outlier  is.extreme
<0 rows> (or 0-length row.names)
```

Figure 119 Outliers remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm Nam Can 2011

```
  Method variable statistic          p
  <fct>  <chr>        <dbl>      <dbl>
1 Manual PERC11       0.978 0.335
2 Survey PERC11       0.876 0.00000333
```

Figure 120 Shapiro-Wilk test remote sensing-based manually delineated mangrove cover (n=60) vs estimated (n=73) mangrove cover on-farm Nam Can 2011

```
>   data_SD_MD %>% wilcox_test(PERC11 ~ Method)
# A tibble: 1 × 7
  .y.    group1 group2    n1    n2 statistic        p
* <chr>  <chr>  <chr>  <int> <int>     <dbl>    <dbl>
1 PERC11 Manual Survey    60    73       233 8.21e-19
>   data_SD_MD %>% wilcox_effsize(PERC11 ~ Method)
# A tibble: 1 × 7
  .y.    group1 group2 effsize    n1    n2 magnitude
* <chr>  <chr>  <chr>    <dbl> <int> <int> <ord>
1 PERC11 Manual Survey   0.768    60    73 large
```

Figure 121 Wilcoxon test remote sensing-based manually delineated mangrove cover (n=60) vs estimated (n=73) mangrove cover 2011 Nam Can

```
  Method variable statistic        p
  <fct>  <chr>        <dbl>    <dbl>
1 Manual PERC11       0.940 0.0925
2 Survey PERC11       0.889 0.000163
```

Figure 122 Shapiro-Wilk test remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm production zone Nam Can 2011, (n=82)

```
>  data_SD_MDpd %>% wilcox_test(PERC11 ~ Method)
# A tibble: 1 x 7
  .y.    group1 group2    n1    n2 statistic        p
* <chr>  <chr>  <chr>  <int> <int>     <dbl>    <dbl>
1 PERC11 Manual Survey    30    52        91 3.08e-11
>  data_SD_MDpd %>% wilcox_effsize(PERC11 ~ Method)
# A tibble: 1 x 7
  .y.    group1 group2 effsize    n1    n2 magnitude
* <chr>  <chr>  <chr>    <dbl> <int> <int> <ord>
1 PERC11 Manual Survey   0.734    30    52 large
>
```

Figure 123 Wilcoxon test remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm production zone Nam Can 2011 (n=82)

```
  Method variable statistic      p
  <fct>  <chr>        <dbl>  <dbl>
1 Manual PERC11       0.969 0.512
2 Survey PERC11       0.878 0.0133
```

Figure 124 Shapiro-Wilk test remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm protection zone Nam Can 2011, (n=51)

```
>  data_SD_MDpt %>% wilcox_test(PERC11 ~ Method)
# A tibble: 1 x 7
  .y.    group1 group2    n1    n2 statistic            p
* <chr>  <chr>  <chr>  <int> <int>     <dbl>        <dbl>
1 PERC11 Manual Survey    30    21        19 0.0000000153
>  data_SD_MDpt %>% wilcox_effsize(PERC11 ~ Method)
# A tibble: 1 x 7
  .y.    group1 group2 effsize    n1    n2 magnitude
* <chr>  <chr>  <chr>    <dbl> <int> <int> <ord>
1 PERC11 Manual Survey   0.794    30    21 large
```

Figure 125 Wilcoxon test remote sensing-based manually delineated mangrove cover vs estimated mangrove cover on-farm protection zone Nam Can 2011, (n=51)

Correlation remote sensing-based manually delineated mangrove cover (change) (m^2) and shrimp farm area (m^2) Nam Can

```
  Zone            layer           SF_ID SF_Area X2011.Man X2011_PERC X2019.Man X2019_PERC Change Change2 is.outlier is.extreme
  <fct>           <chr>           <fct>   <dbl>     <dbl>      <dbl>     <dbl>      <dbl>  <dbl>   <dbl> <lgl>      <lgl>
1 Protection Zone Protection Zone 33     96585.    36217.       37.5    42916.       44.4   6.94   6699. TRUE       FALSE
2 Protection Zone Protection Zone 43     83999.    32073.       38.2    24485.       29.1  -9.03  -7589. TRUE       FALSE
```

Figure 126 Mangrove cover outliers

```
  Zone            layer           SF_ID SF_Area X2011.Man X2011_PERC X2019.Man X2019_PERC Change Change2 is.outlier is.extreme
  <fct>           <chr>           <fct>   <dbl>     <dbl>      <dbl>     <dbl>      <dbl>  <dbl>   <dbl> <lgl>      <lgl>
1 Protection Zone Protection Zone 43     83999.    32073.       38.2    24485.       29.1  -9.03  -7589. TRUE       FALSE
```

Figure 127 Outlier remote sensing-based manually delineated mangrove cover (m^2) (X2011.Man) 2011

```
  Zone            layer           SF_ID SF_Area X2011.Man X2011_PERC X2019.Man X2019_PERC Change Change2 is.outlier is.extreme
  <fct>           <chr>           <fct>   <dbl>     <dbl>      <dbl>     <dbl>      <dbl>  <dbl>   <dbl> <lgl>      <lgl>
1 Production Zone Production Zone 2      39803.    16814.       42.2    28004.       70.4   28.1  11190. TRUE       FALSE
2 Production Zone Production Zone 4      42486.    14887.       35.0    22602.       53.2   18.2   7716. TRUE       FALSE
3 Production Zone Production Zone 9      77053.    10605.       13.8    23660.       30.7   16.9  13055. TRUE       FALSE
4 Production Zone Production Zone 16     71280.    17697.       24.8    31517.       44.2   19.4  13820. TRUE       TRUE
5 Production Zone Production Zone 24     75215.    19800.       26.3    35319.       47.0   20.6  15519. TRUE       TRUE
```

Figure 128 Outliers remote sensing-based manually delineated mangrove cover (m^2) (X2019.Man) 2019

```
  Zone            layer           SF_ID SF_Area X2011.Man X2011_PERC X2019.Man X2019_PERC Change Change2 is.outlier is.extreme
  <fct>           <chr>           <fct>   <dbl>     <dbl>      <dbl>     <dbl>      <dbl>  <dbl>   <dbl> <lgl>      <lgl>
1 Production Zone Production Zone 8     162062.    60925.       37.6    29142.       18.0 -19.6  -31783. TRUE       TRUE
2 Protection Zone Protection Zone 33     96585.    36217.       37.5    42916.       44.4   6.94   6699. TRUE       FALSE
3 Protection Zone Protection Zone 59    116962.    22734.       19.4    42837.       36.6  17.2   20103. TRUE       FALSE
```

Figure 129 Outlier shrimp farm area (SF_Area)

```
            layer SF_ID  SF_Area X2011.Man X2011_PERC X2019.Man X2019_PERC    Change   Change2            Zone is.outlier is.extreme
1 Production Zone    29 48488.98  19864.12   40.96626  3089.365   6.371271 -34.59499 -16774.76 Production Zone       TRUE      FALSE
2 Protection Zone    31 45410.54  24282.18   53.47258  4401.882   9.693524 -43.77905 -19880.30 Protection Zone       TRUE      FALSE
```

Figure 130 Outliers change (m^2) (Change2)

```
  Zoning     Year  Disct     perc_MOF NEAR_DIST BufferZone is.outlier is.extreme
  <fct>      <fct> <fct>        <dbl>     <dbl> <fct>      <lgl>      <lgl>
1 Production 2011  Dam Doi          1    11895. EZ         TRUE       FALSE
2 Production 2011  Ngoc Hien        0     9090. EZ         TRUE       FALSE
3 Protection 2011  Phu Tan          0      448. FPZ        TRUE       TRUE
4 Protection 2011  Ngoc Hien       20     2031. BZ         TRUE       FALSE
5 Protection 2011  Phu Tan        100      292. FPZ        TRUE       TRUE
6 Protection 2011  Phu Tan          0     3522. BZ         TRUE       TRUE
7 Protection 2011  Nam Can         30     1857. BZ         TRUE       FALSE
```

Figure 131 Outliers estimated mangrove cover 2011

```
  Zoning     Year  Disct     perc_MOF NEAR_DIST BufferZone is.outlier is.extreme
  <fct>      <fct> <fct>        <dbl>     <dbl> <fct>      <lgl>      <lgl>
1 Production 2022  Ngoc Hien    10        4662. EZ         TRUE       FALSE
2 Production 2022  Nam Can       7.14     5704. EZ         TRUE       FALSE
3 Protection 2022  Phu Tan      10        1350. BZ         TRUE       FALSE
4 Protection 2022  Phu Tan      10        1374. BZ         TRUE       FALSE
```

Figure 132 Outliers estimated mangrove cover 2022

Distance to open water Ca Mau: estimated mangrove cover

```
 kruskal.test(perc_MOF ~ BufferZone, data = data_11_sel)

	Kruskal-Wallis rank sum test

lata:  perc_MOF by BufferZone
Kruskal-Wallis chi-squared = 8.2173, df = 2, p-value = 0.01643
```

Figure 133 Kruskal Wallis test distance to open water 2011 Nam Can

```
> pairwise.wilcox.test(data_11_sel$perc_MOF, data_11_sel$BufferZone,
+                      p.adjust.method = "BH")

	Pairwise comparisons using Wilcoxon rank sum test with continuity correc
tion

data:  data_11_sel$perc_MOF and data_11_sel$BufferZone

    BZ    EZ
EZ  0.013 -
FPZ 0.740 0.740

P value adjustment method: BH
```

Figure 134 Pairwise comparisons distance to open water 2011 Nam Can

```
> kruskal.test(perc_MOF ~ BufferZone, data = data_22_sel)

	Kruskal-Wallis rank sum test

data:  perc_MOF by BufferZone
Kruskal-Wallis chi-squared = 11.759, df = 2, p-value = 0.002797
```

Figure 135 Kruskal Wallis test distance to open water 2022 Nam Can

```
> pairwise.wilcox.test(data_11_sel$perc_MOF, data_22_sel$BufferZone,
+                      p.adjust.method = "BH")

        Pairwise comparisons using Wilcoxon rank sum test with continuity correc
tion

data:  data_11_sel$perc_MOF and data_22_sel$BufferZone

    BZ   EZ
EZ  0.39 -
FPZ 0.64 0.64

P value adjustment method: BH
```

Figure 136 Pairwise comparisons distance to open water 2022 Nam Can

APPENDIX L – Survey statistics

Do you care about mangroves

```
> tabyl(data_11, Zoning, Answer)
     Zoning no yes NA_
 Production 59  43   3
 Protection 18  18   7
> tabyl(data_22, Zoning, Answer)
     Zoning no yes
 Production 72  20
 Protection 40   6
>
```

Figure 137 Answer summary

Q 2011 vs. 2022

Year	*Answer* no	yes	***Total***
2011	77 55.8 %	61 44.2 %	138 100 %
2022	112 81.2 %	26 18.8 %	138 100 %
Total	189 68.5 %	87 31.5 %	276 100 %

χ^2=19.404 · df=1 · φ=0.273 · p=0.000

Figure 138 Care about mangroves t-T

Q vs. Production Zone

Year	*Answer* no	yes	***Total***
2011	59 57.8 %	43 42.2 %	102 100 %
2022	72 78.3 %	20 21.7 %	92 100 %
Total	131 67.5 %	63 32.5 %	194 100 %

χ^2=8.288 · df=1 · φ=0.218 · p=0.004

Figure 139 Care about mangroves a-A

Q vs. Protection Zone

Year	*Answer* no	yes	***Total***
2011	18 50 %	18 50 %	36 100 %
2022	40 87 %	6 13 %	46 100 %
Total	58 70.7 %	24 29.3 %	82 100 %

χ^2=11.598 · df=1 · φ=0.403 · p=0.001

Figure 140 Care about mangroves b-B

Q vs. Forest Management Zones 2011

Zoning	*Answer* no	yes	***Total***
Production	59 57.8 %	43 42.2 %	102 100 %
Protection	18 50 %	18 50 %	36 100 %
Total	77 55.8 %	61 44.2 %	138 100 %

$\chi^2=0.384 \cdot df=1 \cdot \varphi=0.069 \cdot p=0.536$

Figure 141 Care about mangroves a-b

Q vs. Forest Management Zones 2022

Zoning	*Answer* no	yes	***Total***
Production	72 78.3 %	20 21.7 %	92 100 %
Protection	40 87 %	6 13 %	46 100 %
Total	112 81.2 %	26 18.8 %	138 100 %

$\chi^2=1.001 \cdot df=1 \cdot \varphi=0.105 \cdot$ Fisher's $p=0.255$

Figure 142 Care about mangroves A-B

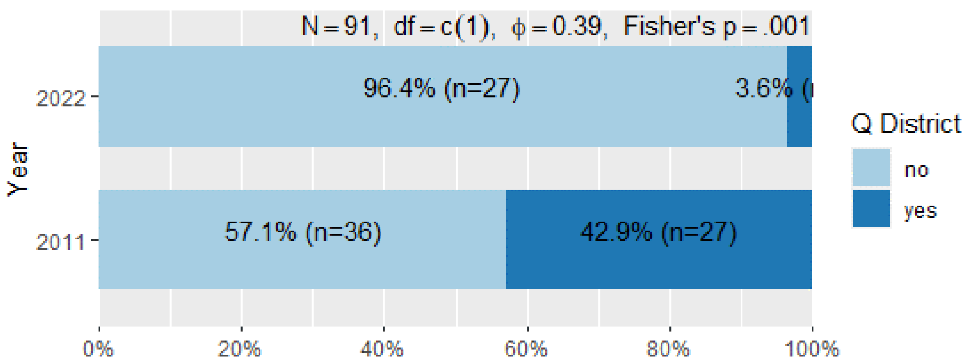


Figure 143 Care about mangroves d-D

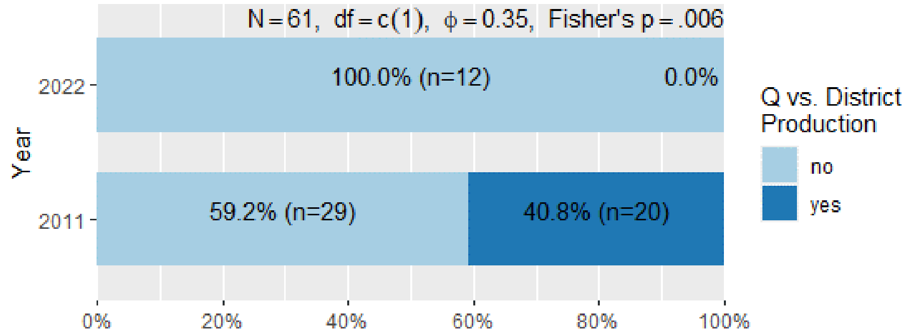


Figure 144 Care about mangroves aD-AD

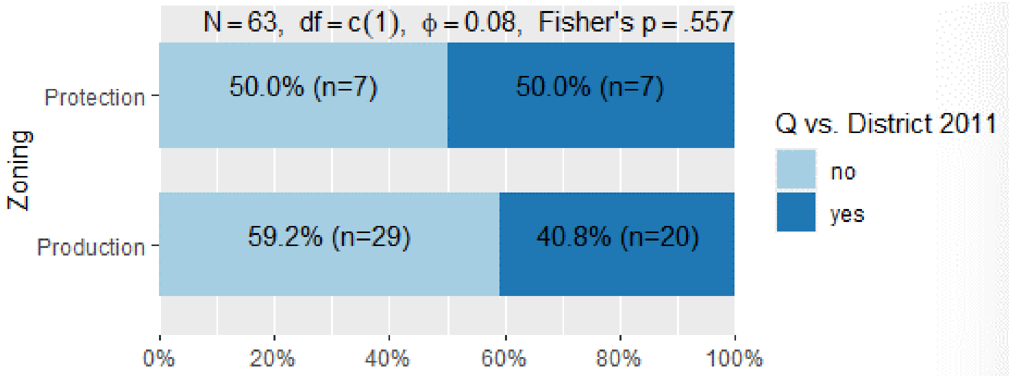


Figure 145 Care about mangroves aD-bD

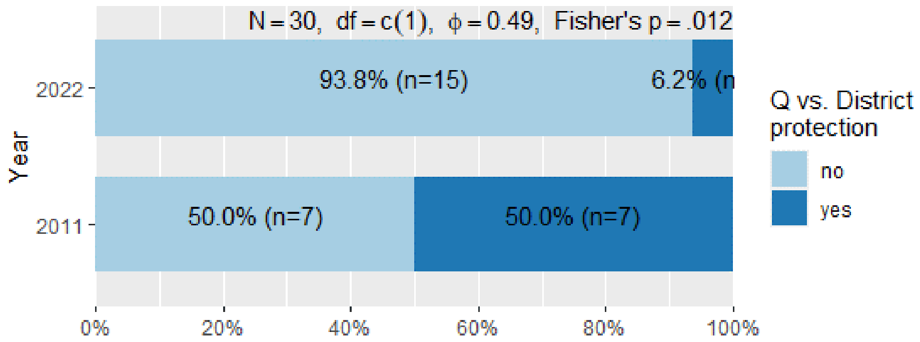


Figure 146 Care about mangroves bd-BD

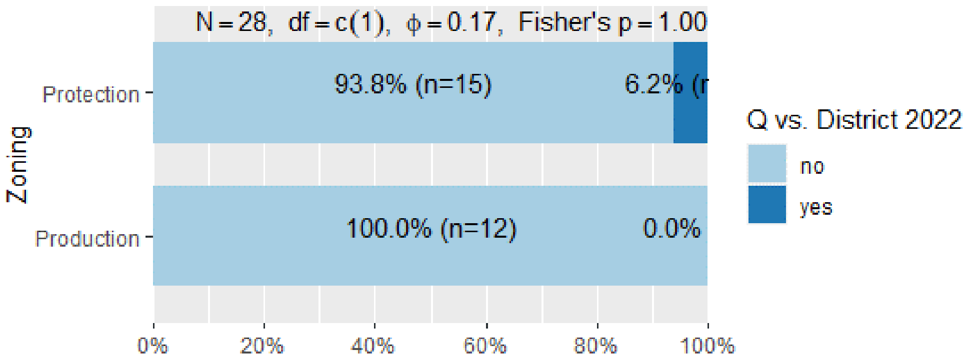


Figure 147 Care about mangroves AD-BD

Do you benefit most of forest exploitation, aquaculture, or both?

```
> tabyl(data_11, Zoning, Answer)
     Zoning aquaculture both NA_
 Production          86    6  13
 Protection          33    2   8
> tabyl(data_22, Zoning, Answer)
     Zoning aquaculture both
 Production          92    0
 Protection          45    1
```

Figure 148 Answer summary

Q 2011 vs. 2022

Year	*Answer* aquaculture	both	***Total***
2011	119 93.7 %	8 6.3 %	127 100 %
2022	137 99.3 %	1 0.7 %	138 100 %
Total	256 96.6 %	9 3.4 %	265 100 %

χ^2=4.680 · df=1 · φ=0.154 · Fisher's p=0.016

Figure 149 Benefit more of aquaculture or both t-T

Q vs. Production Zone

Year	*Answer* aquaculture	both	***Total***
2011	86 93.5 %	6 6.5 %	92 100 %
2022	92 100 %	0 0 %	92 100 %
Total	178 96.7 %	6 3.3 %	184 100 %

χ^2=4.307 · df=1 · φ=0.184 · Fisher's p=0.029

Figure 150 Benefit more of aquaculture or both a-A

Q vs. Protection Zone

Year	*Answer* aquaculture	both	***Total***
2011	33 94.3 %	2 5.7 %	35 100 %
2022	45 97.8 %	1 2.2 %	46 100 %
Total	78 96.3 %	3 3.7 %	81 100 %

χ^2=0.059 · df=1 · φ=0.093 · Fisher's p=0.575

Figure 151 Benefit more of aquaculture or both b-B

Q vs. Forest Management Zones 2011

Zoning	*Answer* aquaculture	both	***Total***
Production	86 93.5 %	6 6.5 %	92 100 %
Protection	33 94.3 %	2 5.7 %	35 100 %
Total	119 93.7 %	8 6.3 %	127 100 %

χ^2=0.000 · df=1 · φ=0.015 · Fisher's p=1.000

Figure 152 Benefit more of aquaculture or both a-b

Q vs. Forest Management Zones 2022

Zoning	*Answer* aquaculture	both	***Total***
Production	92 100 %	0 0 %	92 100 %
Protection	45 97.8 %	1 2.2 %	46 100 %
Total	137 99.3 %	1 0.7 %	138 100 %

χ^2=0.126 · df=1 · φ=0.121 · Fisher's p=0.333

Figure 153 Benefit more of aquaculture or both A-B

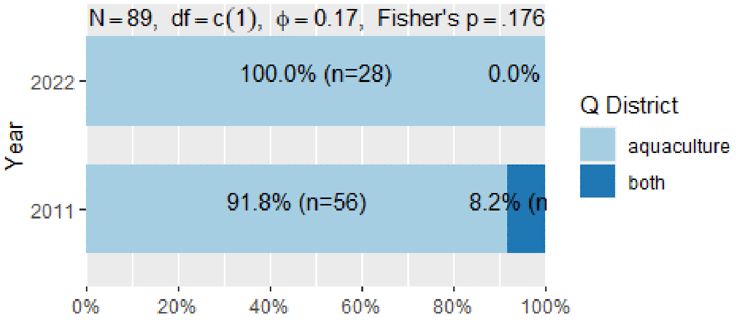


Figure 154 Benefit more of aquaculture or both d-D

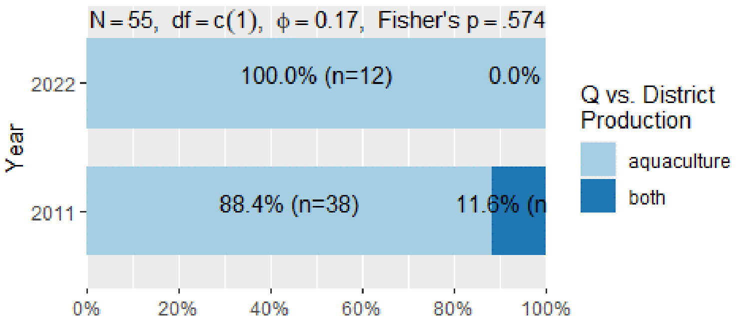


Figure 155 Benefit more of aquaculture or both ad-AD

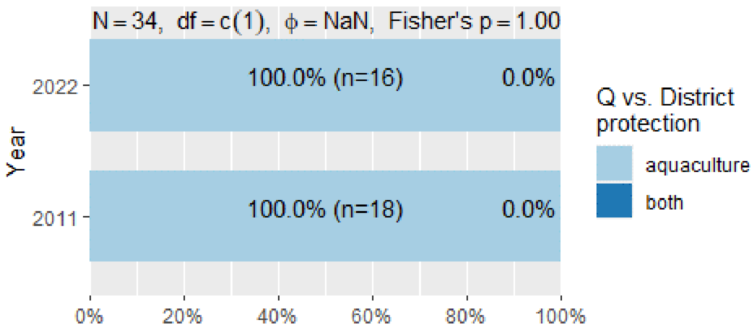


Figure 156 Benefit more of aquaculture or both bd-BD

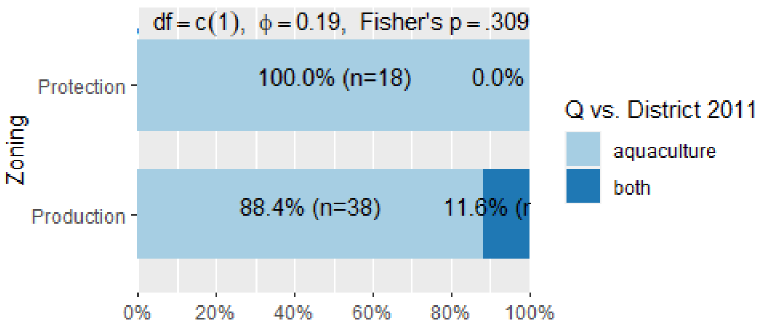


Figure 157 Benefit more of aquaculture or both aD-bD

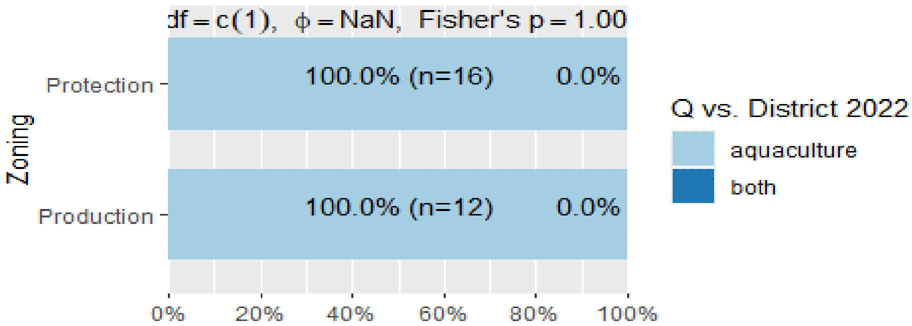


Figure 158 Benefit more of aquaculture or both AD-BD

Do you think this construction wood extraction in your land is allowed (legally)?

```
> tabyl(data_11, Zoning, Answer)
     Zoning no yes NA_
 Production 41  41  23
 Protection 25   8  10
> tabyl(data_22, Zoning, Answer)
     Zoning no yes NA_
 Production 30  61   1
 Protection 23  22   1
```

Figure 159 Do you think construction wood extraction is legal answers distribution

Q 2011 vs. 2022

Year	*Answer* no	*Answer* yes	***Total***
2011	66 57.4 %	49 42.6 %	115 100 %
2022	53 39 %	83 61 %	136 100 %
Total	119 47.4 %	132 52.6 %	251 100 %

χ^2=7.757 · df=1 · φ=0.184 · p=0.005

Figure 160 Do you think construction wood extraction is legal t-T

Q vs. Production Zone

Year	*Answer* no	*Answer* yes	***Total***
2011	41 50 %	41 50 %	82 100 %
2022	30 33 %	61 67 %	91 100 %
Total	71 41 %	102 59 %	173 100 %

χ^2=4.492 · df=1 · φ=0.173 · p=0.034

Figure 161 Do you think construction wood extraction is legal a-A

Q vs. Protection Zone

Year	Answer: no	Answer: yes	Total
2011	25 75.8 %	8 24.2 %	33 100 %
2022	23 51.1 %	22 48.9 %	45 100 %
Total	48 61.5 %	30 38.5 %	78 100 %

$\chi^2=3.900 \cdot df=1 \cdot \varphi=0.250 \cdot p=0.048$

Figure 162 Do you think construction wood extraction is legal b-B

Q vs. Forest Management Zones 2011

Zoning	Answer: no	Answer: yes	Total
Production	41 50 %	41 50 %	82 100 %
Protection	25 75.8 %	8 24.2 %	33 100 %
Total	66 57.4 %	49 42.6 %	115 100 %

$\chi^2=5.374 \cdot df=1 \cdot \varphi=0.236 \cdot p=0.020$

Figure 163 Do you think construction wood extraction is legal a-b

Q vs. Forest Management Zones 2022

Zoning	Answer: no	Answer: yes	Total
Production	30 33 %	61 67 %	91 100 %
Protection	23 51.1 %	22 48.9 %	45 100 %
Total	53 39 %	83 61 %	136 100 %

$\chi^2=3.440 \cdot df=1 \cdot \varphi=0.175 \cdot p=0.064$

Figure 164 Do you think construction wood extraction is legal A-B

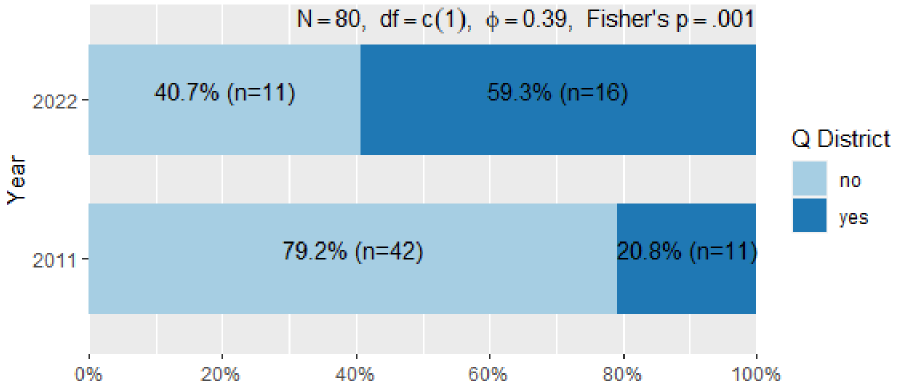


Figure 165 Do you think construction wood extraction is legal d-D

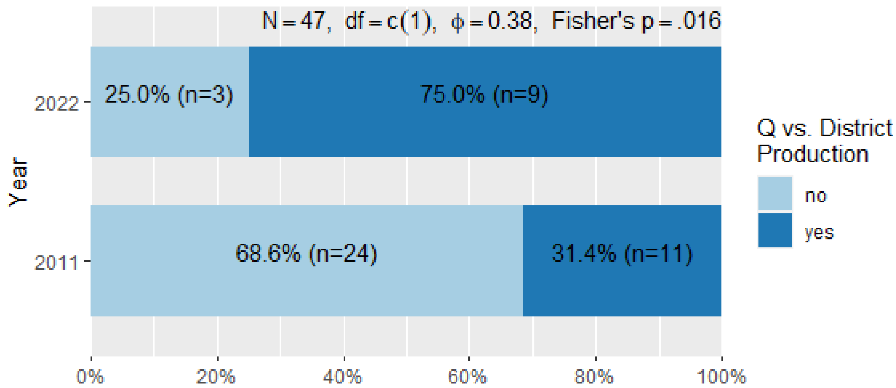


Figure 166 Do you think construction wood extraction is legal ad-AD

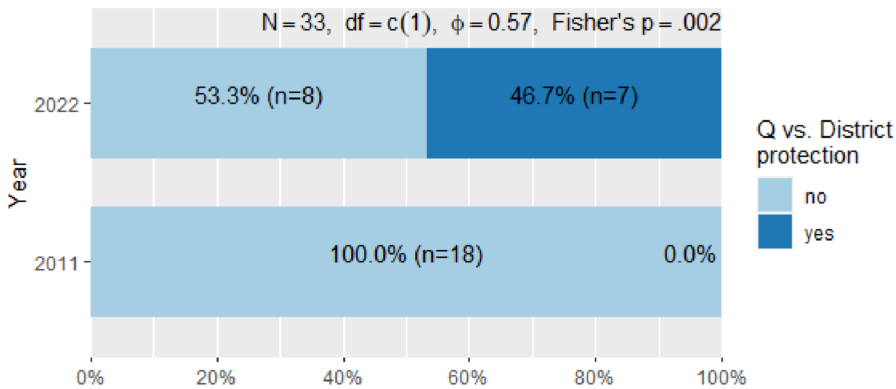


Figure 167 Do you think construction wood extraction is legal bD-BD

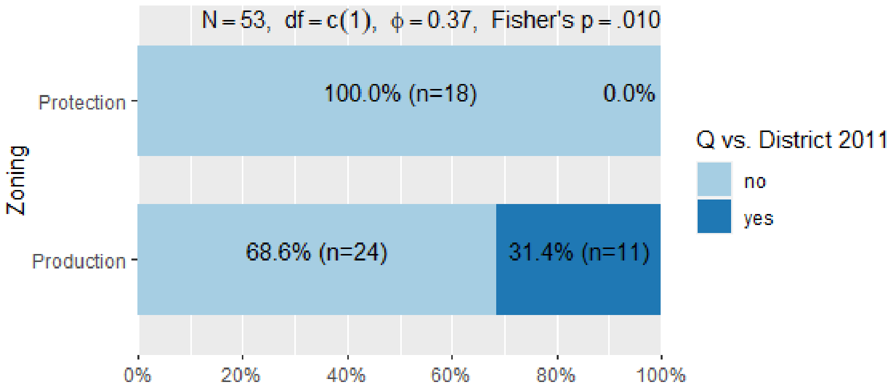


Figure 168 Do you think construction wood extraction is legal aD-bD

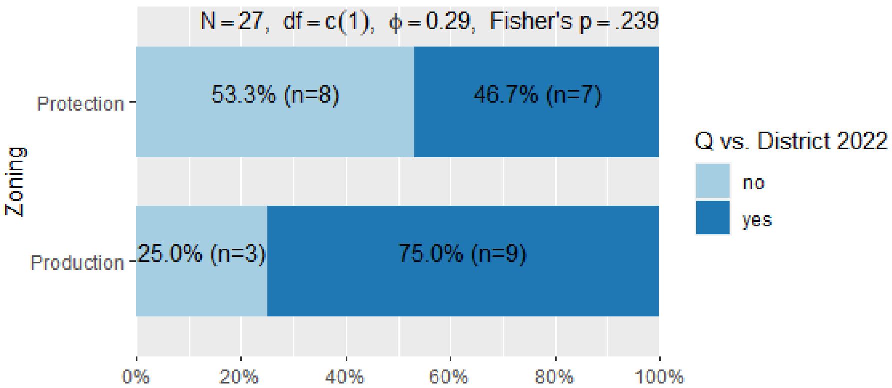


Figure 169 Do you think construction wood extraction is legal AD-BD

Do you think this fuelwood extraction in your land is allowed (legally)?

```
> tabyl(data_11, Zoning, Answer)
     Zoning no yes NA_
 Production 22  66  17
 Protection 11  20  12
> tabyl(data_22, Zoning, Answer)
     Zoning no yes NA_
 Production 32  58   2
 Protection 20  25   1
```

Figure 170 Do you think fuel wood extraction is legal answers distribution

Q 2011 vs. 2022

Year	*Answer* no	*Answer* yes	***Total***
2011	33 27.7 %	86 72.3 %	119 100 %
2022	52 38.5 %	83 61.5 %	135 100 %
Total	85 33.5 %	169 66.5 %	254 100 %

χ^2=2.839 · df=1 · φ=0.114 · p=0.092

Figure 171 Do you think fuel wood extraction is legal t-T

Q vs. Production Zone

Year	*Answer* no	*Answer* yes	***Total***
2011	22 25 %	66 75 %	88 100 %
2022	32 35.6 %	58 64.4 %	90 100 %
Total	54 30.3 %	124 69.7 %	178 100 %

χ^2=1.873 · df=1 · φ=0.115 · p=0.171

Figure 172 Do you think fuel wood extraction is legal a-A

Q vs. Protection Zone

Year	*Answer* no	*Answer* yes	***Total***
2011	11 35.5 %	20 64.5 %	31 100 %
2022	20 44.4 %	25 55.6 %	45 100 %
Total	31 40.8 %	45 59.2 %	76 100 %

χ^2=0.296 · df=1 · φ=0.090 · p=0.587

Figure 173 Do you think fuel wood extraction is legal b-B

Q vs. Forest Management Zones 2011

Zoning	*Answer* no	*Answer* yes	***Total***
Production	22 25 %	66 75 %	88 100 %
Protection	11 35.5 %	20 64.5 %	31 100 %
Total	33 27.7 %	86 72.3 %	119 100 %

χ^2=0.789 · df=1 · φ=0.103 · Fisher's p=0.351

Figure 174 Do you think fuel wood extraction is legal a-b

Q vs. Forest Management Zones 2022

Zoning	*Answer* no	*Answer* yes	***Total***
Production	32 35.6 %	58 64.4 %	90 100 %
Protection	20 44.4 %	25 55.6 %	45 100 %
Total	52 38.5 %	83 61.5 %	135 100 %

$\chi^2=0.661 \cdot df=1 \cdot \varphi=0.086 \cdot p=0.416$

Figure 175 Do you think fuel wood extraction is legal A-B

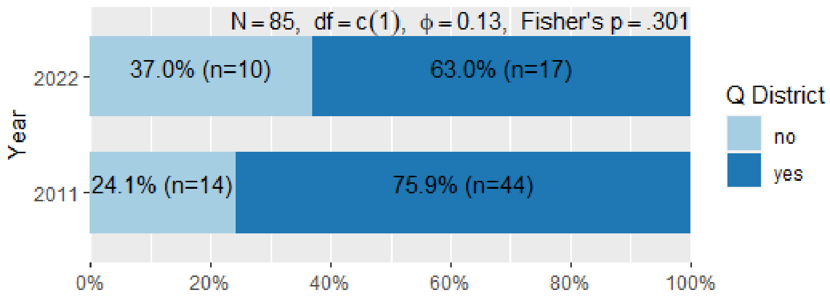


Figure 176 Do you think fuel wood extraction is legal d-D

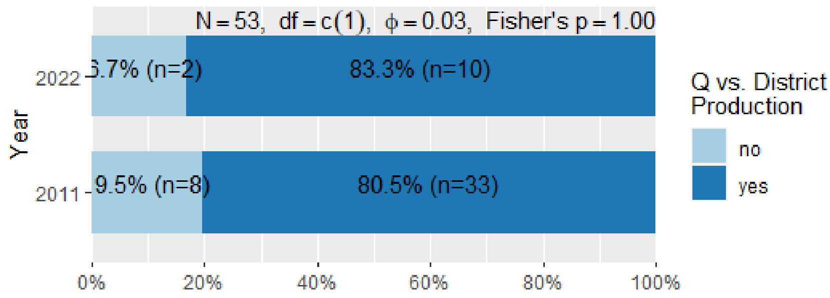


Figure 177 Do you think fuel wood extraction is legal ad-AD

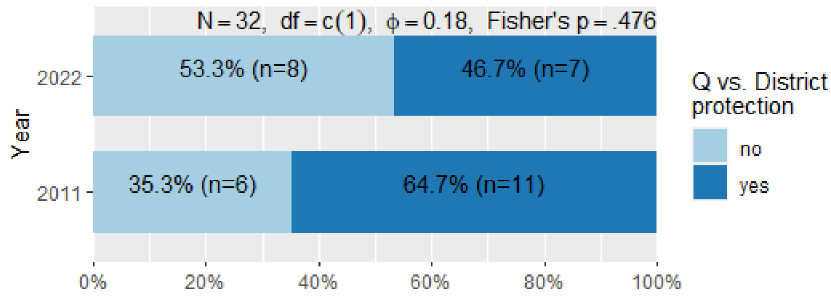


Figure 178 Do you think fuel wood extraction is legal bd-BD

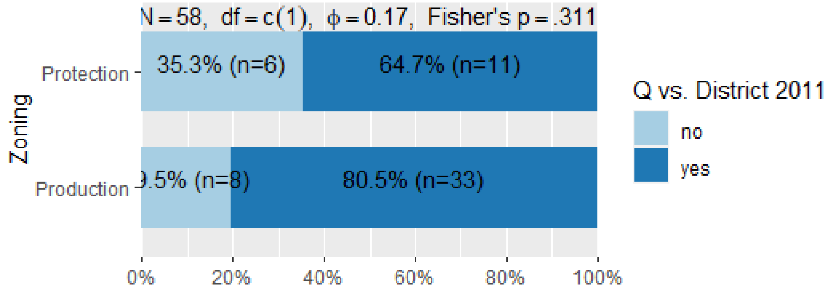


Figure 179 Do you think fuel wood extraction is legal aD-bD

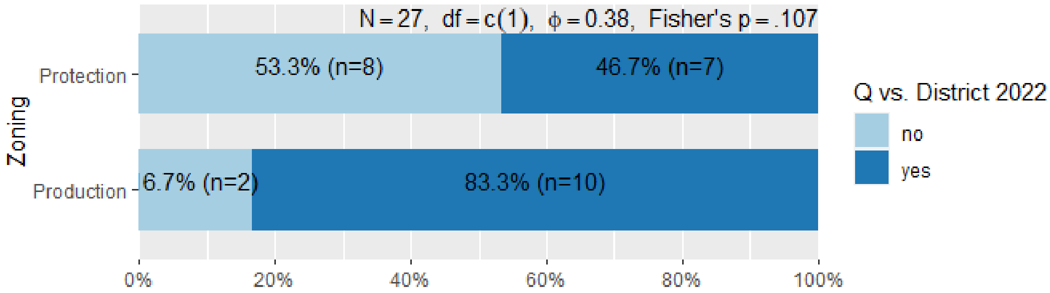


Figure 180 Do you think fuel wood extraction is legal AD-BD

APPENDIX M – Order area at European Space Agency (ESA)

Figure 181 Order area Quickbird 2011 satellite imagery at ESA

Figure 182 Order area GeoEye 2019 satellite imagery at ESA

APPENDIX N – Example manual segmentation, shadow

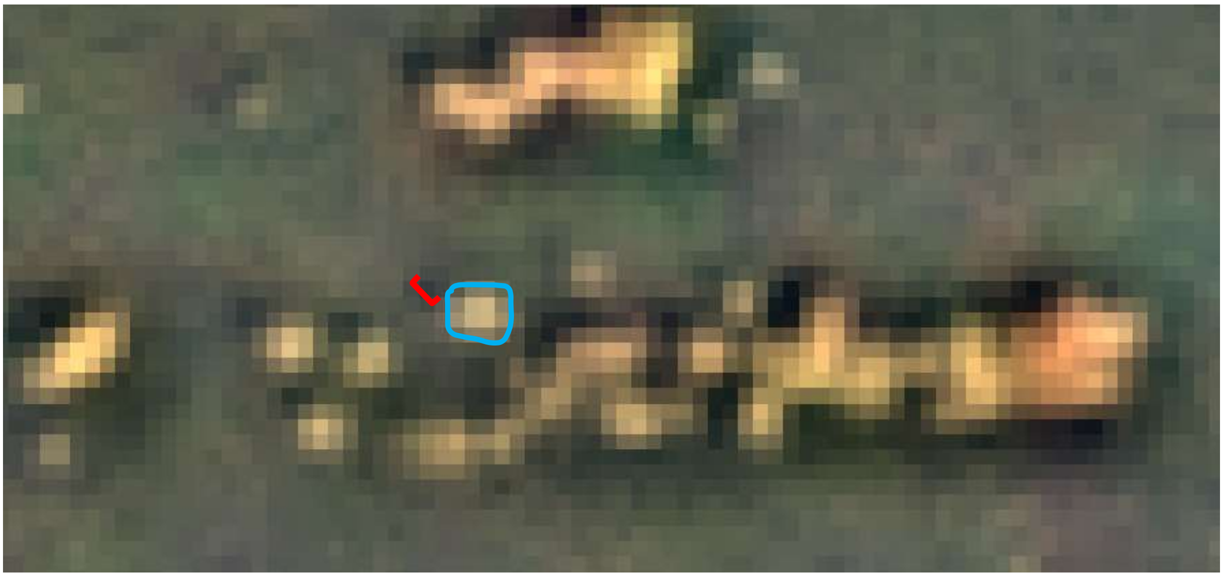


Figure 183 Manual delineation example. Example of the Quickbird 2011 imagery. The red bracket indicates a mangrove propagule with less than 3 pixels of shadow. This would be classified as a propagule polygon (see blue outline).

Note (from Methods Section)- With a mean sun elevation of 52.1 ('e') in both cases, the minimum shadow length can be determined as 1.2845 meters using the formula 1/tan (52.1). Considering the pixel sizes of the satellite images, it is necessary to detect at least three pixels of shadow for 0.5 resolution (equivalent to 1.5 meters of shadow), and at least four pixels for 0.4 resolution (equivalent to 1.6 meters of shadow). This analysis allows us to classify mangrove trees of at least 1.9 meters tall in the 2011 image and 2.1 meters tall in the 2022 image, almost double the required height. However, using fewer shadow pixels could lead to the incorrect classification of mangroves that have not yet reached the required height, leading to an overestimation.