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Towards sustainable seaweed aquaculture in Nosy Boraha, Madagascar: Insights from social and ecological sciences

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Abstract

Cottonii seaweed (*Kappaphycus alvarezii)* farming is a growing activity in Madagascar, promoted as part of the country's blue economy strategy for sustainable development. Despite its expansion, few interdisciplinary studies have simultaneously examined its environmental, social, and legal dimensions. In 2024, we conducted an interdisciplinary study in Nosy Boraha, where seaweed aquaculture is rapidly developing. Combining anthropology, marine ecology, and environmental law, the research aimed to assess the effects of seaweed farming on local communities, describe the lagoon's environmental characteristics and benthic habitats, and analyse the legal framework governing the activity, including national legislation and local customary law (Dina). The results indicate that seaweed farming provides an important supplementary livelihood for residents of Ilampy and nearby villages, particularly as fisheries resources decline. However, farmers reported challenging working conditions and expressed concerns about potential impacts on coral reefs and traditional fishing grounds. Remote sensing analyses using satellite and drone imagery estimated the north reef lagoon at approximately 600 ha. This shallow environment (<5 m) is dominated by sandy substrates and macrophytes, we have identified four seagrass and three macroalgal genera in the seaweed cultivation areas. Coral communities, comprising roughly four genera, are mainly concentrated near the reef crest. The company Nosy Boraha Seaweed operates across about 300 ha of the lagoon, although cultivation plots cover only 8.3% of this area. Nutrient analyses showed uptake of

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dissolved inorganic nitrogen and phosphates both within farming zones and in control areas without seaweed cultivation. Finally, the local Dina, grounded in the *Fihavanana* principle of solidarity and reciprocity, plays a central role in marine resource management. It operates alongside formal governance structures led by local fisheries committees and Madagascar's Environmental and Blue-Economy Ministries.

Author summary

Our research aims to establish a baseline for assessing the sustainability of seaweed aquaculture at Nosy Boraha (Sainte-Marie Island), Madagascar. An interdisciplinary team of anthropologists, reef ecologists, chemists, and environmental law specialists collaborated to characterise the reef socio-ecosystem in which seaweed farming operates and to examine the legal frameworks governing the activity, including both national regulations and customary law (Dina). This study draws on field investigations conducted in 2024. We provide new insights into the effects of seaweed farming in Ilampy and nearby villages, highlighting its contribution to local livelihoods amid declining fisheries. At the same time, we describe the environmental setting of the north-east lagoon, where cultivation occurs, including its physico-chemical conditions and benthic communities. The ecosystem is dominated by seagrass and macroalgae, while nutrient concentrations are low, consistent with oligotrophic tropical environments. These findings suggest that seaweed farming currently operates within a relatively nutrient-poor but ecologically sensitive system. Overall, our results show that the governance of seaweed aquaculture combines national legislation with the locally enforced Dina, reflecting a hybrid legal framework. This integrated approach is particularly significant in the context of accelerating blue-economy development in coastal regions, especially in low- and middle-income countries such as Madagascar.

1. Introduction

Seaweed has a considerable worldwide potential, yet it remains under-exploited in many regions. When cultivated sustainably, macroalgae can provide multiple ecosystem services, including food provision, marine ecosystem restoration, social development, and contributions to reducing greenhouse gas emissions through applications such as plastic substitution and low-carbon economy initiatives [1–6]. For these reasons, seaweed aquaculture as an important pathway to take action for several United Nations Sustainable Development Goals (SDGs), particularly SDGs: 1 -*No poverty*-, 2 -*Zero hunger*-, 8 -*Decent work and economic growth*-, and 13 -*Climate action*-. This potential, has driven rapid global growth in the sector, with demand for seaweeds and derived products increasing by an average of 6.2% per year between 2000 and 2018 [4,7,8]. Aquaculture now accounts for 51.3% of marine and coastal

production worldwide [9]. International initiatives, such United Nations Global Seaweed Initiative, further emphasise the sector's relevance.

In the tropics, seaweed aquaculture is dominated by Southeast Asian and East African [7,8]. In the Western Indian Ocean (WIO), the cultivation of *Kappaphycus sp* (Cottonii) and *Eucheuma sp* offers promising blue economy opportunities and livelihoods, notably for women [8,10–12]. In 2022, Madagascar contributed 4,7% of East-Africa seaweed production, following Zanzibar, which produces 92% among 13 African countries producing seaweed [8,13]. While seaweed aquaculture in Madagascar is flourishing, it also presents social, economic, and environmental challenges. As the fifth-largest island and the ninth-poorest country, with a gross domestic product per capita of around $3 per day (*World Economic Outlook, 2024*), Madagascar is both a marine biodiversity hotspot [13] and also highly vulnerable to climate change. Reconciling ecosystem conservation with the expansion of blue activities is therefore critical. To support sustainable development, Madagascar's environmental legal framework combines state laws with regional customary rules, known as Dina [14,15]. Customary laws are adapted to local contexts, while state laws apply nationwide. This dual framework facilitates collaboration among the Ministry of the Environment, the Ministry of Blue Economy, the Ministry of Agriculture, Livestock and Fisheries, and local stakeholder groups, for management of natural resources and the development of blue-economy activities.

Social and ecological risks of seaweed aquaculture remain poorly understood globally. Spillias et al. (2022, 2023) [16,17] reviewed 186 studies and highlighted that most studies focus on a few algal species and limited regions. Twenty key social and environmental effects have been identified to monitor, including water quality, algal blooms, biodiversity, hydrodynamics, livelihoods, culture, and community resilience. They emphasised the need for appropriate management, including regulatory and mitigation measures, to ensure a fair and sustainable industry [17]. So far, seaweed farming is generally considered beneficial for local livelihoods in low- and middle income countries [9,12] and to have lower environmental impact compared with other types of aquacultures [18]. However, seaweed farms can modify local environments, particularly shallow (<25 m) or very shallow (<5 m) coastal habitats such as seagrass meadows and coral reefs [19–21]. Observed impacts include reduced seagrass biomass, sparser meadows, a lower carbon storage, and in some cases complete habitat loss primarily due to mechanical degradation (stomping, uprooting) and shading from farm structures, as documented in Zanzibar, Kenya, Madagascar [12,22]. In some contexts, farmed red algae became invasive, Conklin et al. (2005) [23] reported smothering and shading of reef-building corals, occasionally causing extensive coral mortality. Such risks have prompted bans on the cultivation of certain seaweed species in countries including India and the USA (Hawaii). Studies combining social and environmental aspects are scarce.

Several recent studies recommend an interdisciplinary approach to evaluate the sustainability of seaweed aquaculture [4,7,17]. Key factors such site-specific features, scale and activity intensity must be considered to provide recommendations, and mitigation measures for potentials socio-ecological impacts. However, interdisciplinary research presents challenges and requires flexibility, mutual respect, trust, patience, humility, persistence, collaboration and faces difficulties such as limited fieldwork time, incompatible sampling plans, and unequal power dynamics among participants [24–26]. Overall, it is a long-term process that demands curiosity, specific expertise, and sustained patience [27]. To our knowledge, no interdisciplinary studies have yet addressed the effects of seaweed farming on Malagasy reef socio-ecosystems. The few existing studies, such Ateweberhan (2014), Todinanahary et al. (2016, 2017) and Mollion et al. (2020) [22,28–30] focused primally on the South-Western region of Madagascar (Antisimo Andrefana) and in seaweed inventory. These studies showed that seaweed aquaculture improves greatly livelihoods, particularly that of women. Also they identified environmental factors affecting Cottonii growth, but social and ecological aspects were largely investigated separately.

In this context, our main goal is to establish a baseline for assessing the sustainability of seaweed farming at Nosy Boraha (Sainte-Marie Island) - Madagascar, where Cottonii aquaculture has expanded rapidly since 2021. Our study question: *Does seaweed aquaculture represent a sustainable development opportunity? Or, does it pose risk of conflict for local communities and ecosystem conservation?* To address this, anthropologists, reef ecologists, chemists and

environmental law specialists collaborated together and establish intersectoral partnerships with local stake holders, seaweed companies, NGOs, and local associations representing communities involved in the activity.

2. Results

2.1. Anthropological results

Our results are presented mainly for Ilampy village, but ethnographic surveys were also conducted at nearby villages: Ankobahoba and Ambodifotatra (Nosy Boraha capital) as they represent also communities involved in seaweed activities. Ilampy is a coastal village (fokontany) located in the circumscription of Ambodifotatra on the eastern coast of Nosy Boraha. The village has approximately 5,000 inhabitants and is characterised by a strong social cohesion and subsistence-based way of life, notably fishing, agriculture, and seaweed farming, which has become the main livelihood since 2015 (Interviews: chief fokotany, village inhabitant and companies director's. 'Farming of Cottonni began in Nosy Boraha in 2015 thanks to a businessman Thierry. He launched a pilot project to test seaweed cultivation in four villages: Ilampy, Lohatrozo, Anivorano, and Vohilava. Ilampy emerged as the most favourable site due to its lagoon and natural conditions'). Social organisation is strongly influenced by *Fihavanana* (Le Fihavanana à Madagascar: Lien Social Et Économique Des Communautés Rurales. Frédéric SANDRON 2008. Revue Tiers du Monde, N° 195-Juilliet-septembre, p. 507–522.), a core Malagasy cultural principle centred on mutual aid, solidarity and social harmony. This concept underpins community management practices on Nosy Boraha and provides mechanisms for conflict resolution. Local associations such *'Ankobaoba Villages des Algues'* (AVA) bring together seaweed farmers and play a key role in organising the sector. These associations act as intermediaries between companies and local communities and also provide social supports services, including access to loans (Fig 1)

2.1.1. Socio-economic insights. Overall, observation and interviews of habitants related that seaweed farming has significantly improved local livelihoods and quality of life (S1 Appendix- quotations). In 2024, the sector generated approximately two billion Malagasy Ariary (MGA) in revenue, with an average monthly income of around one million MGA per seaweed farmer, while employees received 1.6 billion MGA in wages. Increased income has enabled investment in housing and infrastructure and strengthened social cohesion through mutual support and self-help groups (Sources: semi-structured interviews, immersive participant observation, conference 'L'Algoculture à Sainte-Marie' Nosy Boraha Seaweed company director, S. Jan- October 2024.) (S1 Appendix 1.1-1.2).

All interviewees reported income improvements, and many households diversified their livelihoods by combining seaweed farming with fishing, rice cultivation, or petty trade. Socially, tasks are gendered: women are primarily responsible for seaweed cutting (Fig 1-b), enhancing their economic autonomy and role in household decision-making (S1 Appendix 1.3), while men mainly conduct harvesting at sea and post-harvest processing, (Fig 1-a, c, d). Although most stakeholders expressed high satisfaction, some concerns were raised regarding production quotas, administrative delays, and inadequate infrastructure, the President of AVA association indicated that: *"We can't allow everyone to become an seaweed farmer because of organizational limitations in the companies"* (S1 Appendix 1.2-1.6). The activity has strengthened communities, seaweed farmers help each other with complex tasks, such as repairing ropes or installing cuttings. This solidarity has also led to the creation of self-help groups, where everyone exchanges tips on crop management and maintenance.

2.1.2. Socio-cultural factors and belief practices. Ilampy maintains strong ancestral traditions, including ritual practices such *Valintafa* - zebu sacrifices (i.e.Valintafa: Sacred rite of the Saints marians in which a zebu is sacrificed to thank the spirits after a vow has been granted. This is often a second sacrifice, in response to a first one in which the vow was made) which coexist with daily subsistence activities. Local cultural adoption an practices have been essential to the acceptance of seaweed farming with companies actively participating in local social and cultural life while respecting *Fady* (taboos). Traditional ceremonies, including zebu sacrifices, have marked key stages in the development of seaweed farming, first for the initial vow, to ensure the success of seaweed farming, a second one as 'expiatory sacrifice' was made



Fig 1. Ethnographic survey: selection of images illustrating key actions and observations. (a) Planting of seaweed cuttings in the reef lagoon; **(b)** Seaweed cutting by a team composed exclusively of women; **(c)** Weighing of freshly harvested seaweed and drying tables; **(d)** Compaction of dry seaweed; **(e)** Programme kick-off meeting involving 17 villages (fokotany) representatives, the local fisheries committee, local partner NGOs: GRET (Groupe de Recherche et d'Échanges Technologiques) and Platform of consultation and support for the sustainable development of Sainte-Marie island (PCADDISM), and seaweed company managers.

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to appease spirits during a green algae bloom episode that temporally stopped the seaweed activity, and a third one to express gratitude and celebrate improved conditions. Financial support from seaweed companies for cultural events (e.g., finance the purchase of zebu cattle for sacrifices) has further strengthened community relations, demonstrating how local belief systems facilitate the integration of seaweed farming into social dynamics.

2.1.3. Environmental concerns. As it results from the interviews, concerns from fisherman committee were raised about potential coral reef degradation in specific zones linked to poorly regulated farming practices. A perceived decline in octopus population has also been reported by fishermen, possibly linked to the expansion of farming areas and increased

human movement across reef and lagoon zones. These observed impacts contribute to the potential conflict in marine spatial management related to this new blue economy activity (S1 Appendix 1.6). However, seaweed farming has reduced fishing pressure in the lagoon and may have contributed to habitat recovery in some areas. As it provides partially year-round income, it offers an important alternative for fishermen facing declining fish stocks. They therefore diversified their activities to insure a year-round quality of life for their family, Julino: *"Before, I was just a fisherman with few resources. Now, I can send my children to school and offer them a better future"* (S1 Appendix 1.3).

2.1.4. Governance and management of marine resources. Literature review (Unpublished literature & institutional documents (non exhaustive list): Plan de Développement de l'Algoculture- Ministry of Agriculture, livestock and fisheries of Madagascar (MAEP), 2021; Report: A. T., Tatangirafeno, S., Rakotonjanahary, F., Tsiresy, G., Mara, E. R., Eeckhaut, I., & Lavitra, T. (2016). Inventaire et étude de faisabilité de sites propices à l'algoculture, l'holothuriculture, la gestion de l'exploitation de poulpes et de crabes dans la Région Atsimo Andrefana. Rapport d'étude, MHSA – PRU (Contrat n° 166/C/PIC2/2016), 357 p; Report: Inventaire et étude de faisabilité des sites propices à l'algoculture dans la région d'Atsimo-Andrefana. Mentionné pour l'équilibre entre régulations coutumières et modernes dans l'accès aux ressources marines, ainsi que pour les recommandations sur la cogestion participative (2020) pp. 3–12).) and fieldwork highlight the importance of participatory governance in the managing seaweed farming and marine resources. At Nosy Boraha, management is shaped by a combination of customary codes and modern regulations, but local participation remains limited due to power imbalances involving authorities and private companies. Access to marine space and resources has become often a source of conflict among fishermen, seaweed farmers and in some case with tourist operators (mainly represent by hotel industry). While many residents wish to engage in seaweed farming, limited farm availability creates frustration, though conflicts remain mostly low-intensity. The most significant tensions between fishermen and seaweed farmers, are mainly due to the activity management driven by company decisions and the absence of a clear spatial marine planning that could regulate resources uses (S1 Appendix 1.6).

2.1.5. Overall perception of seaweed farming. The lexical analysis of anthropology corpus (results and interviews) shown that the most frequent terms primarily relate to economic activity and livelihoods: *activity, farmers, economic, resources*, as well as to social and spatial embeddedness: *local, life, practices, village* (Fig 2, S2 Appendix). This output reflects how people frame and perceive seaweed farming. This lexical distribution suggests that seaweed aquaculture is primarily perceived as a work-based activity embedded in everyday life. The concurrent presence of fishing-related terms further indicates a conceptual coexistence between seaweed farming and small-scale fisheries, without the emergence of an explicit vocabulary of conflict. However, the relative absence of resistance-oriented language should not be understood as an absence of tension, but rather as reflecting socially legitimate ways of speaking and the available frames of expression. Certain concerns, including economic dependency, intra-community tensions, physical hardship, or latent disagreements with governance arrangements, may remain unspoken, not because they lack significance, but due to social, political, or moral constraints.

2.2. Ecology results

2.2.1. Environmental conditions. In the northern lagoon, sea surface temperature ranged from 24.9 ± 0.4°C in winter (July 2024) to 27.7 ± 0.5°C in summer (November 2024). Salinity varied from 33.04 ± 1.21 in winter to 34.38 ± 0.19 in summer (Fig 3, point RN 1C). Drifter deployments (n = 22) revealed spatially variable circulation patterns. In the northern lagoon, current were predominantly onshore and oriented north-east, influenced by the Ampanihy pass and mangrove system, which promotes lagoon - ocean exchange. In contrast, the southern lagoon was characterised by along-shore flowing from south to north (Fig 3).

2.2.2. Reef lagoon occupancy by Nosy Boraha Seaweed activities. A single orthomosaic mapping the overall zone of seaweed farming occupancy within north reef lagoon zone. Of the 145 farms, 92 were actives at the time of the survey (date: 10/24/2024). Approximately 50% of this zone was utilised 300 c. of 600 ha seaweed farms occupying about 8% of



Fig 2. Local perceptions of seaweed farming represented as a word cloud. Font sizes are proportional to term frequency. Colour codes indicate analytical domains: blue – livelihoods and economic aspects; green – social and everyday life; teal – marine and environmental aspects; purple – place-based spatial identity. Terms that do not clearly belong to a single analytical category are shown in grey.

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this area (~ 25 ha) (Fig 4), each farm covered approximately 0.3 ha. The absence of some farms reflects temporary or permanent cessation of activity, dismantling during green algae bloom -notably in the southern zone between July and September-, or displacement following storm events. The farming zone was intensively used by farmers accessing sites on foot, by kayak or pirogue during low tide for seeding, maintenance and harvesting, while biomass collection was mainly conducted using motorised barges. Some farming activities partially overlapped reef associated habitats, particularly mixed seagrasses meadows and macroalgal assemblages zones (*Halophila sp, Caulerpa sp)* within farms areas, and of *Thalassia sp* closer to the shoreline, where fresh seaweed was unloaded at conditioning site (Figs 4 and 5).

Total harvested biomass for October 2024 was estimated at ~590 tonnes across the entire zone, comprising 468 cultivation plots managed by 121 farms. Along radial 1, approximately 96 tonnes were harvested from 77 plots across 18 farms, while along radial 2, 86 tonnes were harvested from 85 plots across 28 farms. During this period, production was strongly affected by green algal bloom episode, which attached to cultivation lines and reduced Cottonii growth. Consequently, recorded biomass does not reflect typical production patterns, which usually show higher yields in the southern zone. The impact of the green algae bloom *'green tide'* was particularly severe in the south, where farming activities were largely suspended for one to two months.

2.2.3. Abiotic and biotic benthic environment. Seaweed farming activities were primarily located on a sandy substrates with sparse seagrass and macroalgae covers (Figs 5 and 6). The dominant seagrass genera were *Thalassia sp* and *Halophila sp* followed by mixed macroalgae assemblages, mainly represented by: *Caulerpa sp, Hydroclathrus sp, Acanthophora sp* (S3 Appendix a, c, d, e). Radial 1 (north) showed a downstream assemblage dominated by mixed sand, seagrass and macroalgae (77%), Fig 5 top-1A; while the mid-lagoon station (1B) corresponded to seaweed farm areas on sandy substrates (S3 Appendix b). Upstream areas (1C), were more diversified, with patchy *Halophila sp* meadows (38%), macroalgae (15.7%), and mineral components, sand and coral rubble 30%, (S3 Appendix h) Fig 5, top-1C. Radial 2 (south) was the most diverse, downstream zone (2A) was mainly sandy (67%) and macroalgae (33%), Fig 5 middle-2A. Mid-lagoon station was dominated by macroalgae (57%), with presence of cyanobacteria (33%), Fig 5 middle-2B

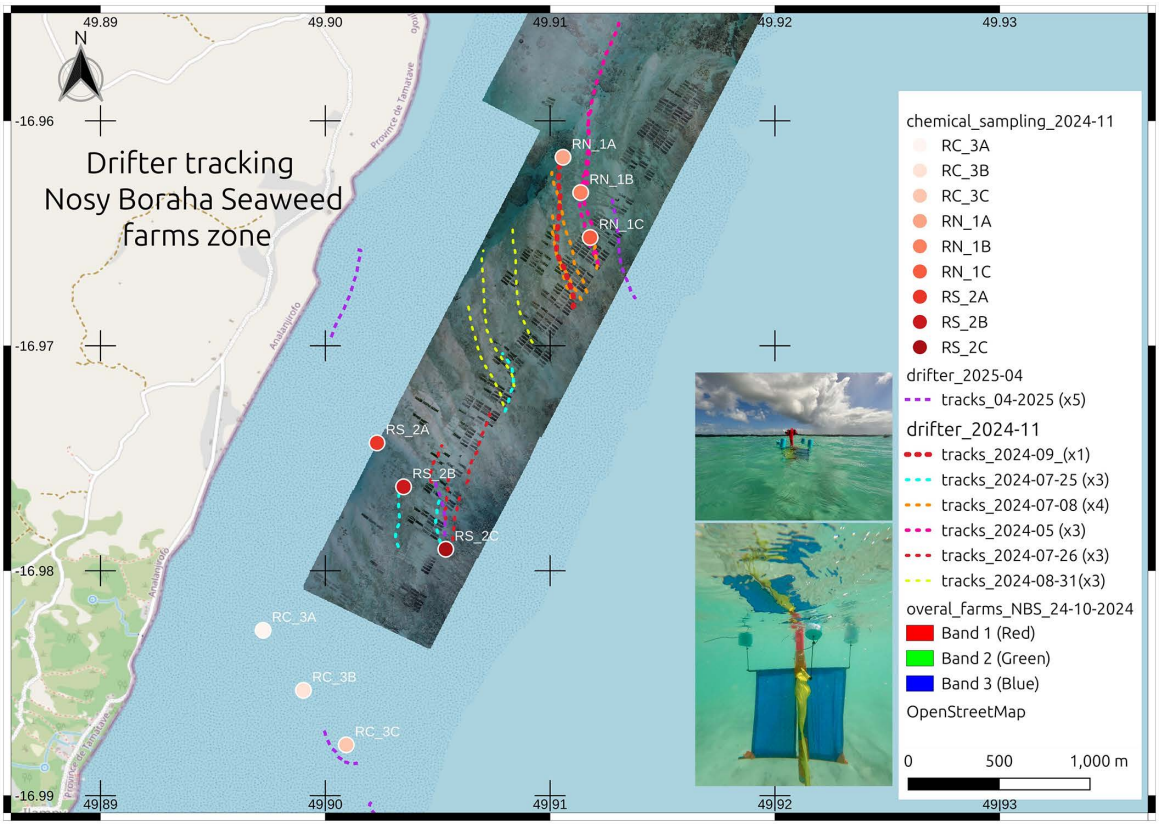


Fig 3. Visualisation of drifter tracks; colours indicate the release date of each drifter. Points represent the locations of chemical sampling along three radials: North, South and Control. The red colour gradation of the points represents the geographical gradient from north to south and reflects the cross-shelf transition from the coastline to the barrier reef for each radial. The orthomosaic is a red–green–blue image. Base map data: OpenStreetMap contributors (https://www.openstreetmap.org), licensed under the Open Database License (ODbL) v1.0 (https://opendatacommons.org/licenses/odbl/1-0/).

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(S3 Appendix f), and the upstream station (2C) near the reef, exhibited corals patches (*Porites sp)* (7.7%) macroalgae (13%), seagrass (*Thalassia sp, Halophila sp)* (3.7%), extensive coral rubble on sandy substrate (71.1%), Fig 5, middle-2C. The control radial (radial 3) showed patterns similar to radial 2 with lower upstream diversity, downstream (3A) and mid-lagoon stations (3B) were dominated by sand, seagrasses, and macroalgae, while upstream zones were largely sandy with limited coral cover, mainly massive *Porites* sp, Fig 5, bottom-3C.

2.2.4. Habitat maps. Seagrasses meadows represented the dominant habitat (~323 ha), including ~40 ha for *Halophila sp*, ~ 138 ha of *Thalassia sp* and ~145 ha of mixed seagrass assemblages. Macroalgae zones ~110 ha, while reef patches occupied ~139 ha, forming a band of 300–600 m wide landward of the reef crest across (Fig 6). Along North radial-1, near-shore areas were dominated by *Thalassia sp* seagrass meadows, followed by deeper channel (~3–4 m depth) whit coral patches, mainly massive corals (*Porites sp).* Seaweed farms were located on a shallow(~500 m wide) sandy band with mixed macroalgae and seagrass. Drone mapping showed that coral communities increased towards the reef crest, with the most diverse assemblages confined to a ~ 350 m-wide crest zone (Fig 6-top). South radial-2 showed higher seagrass diversity nearshore and channel characterized by mixed seagrass meadows and coral patches. The farming zone was largely colonised by benthic macroalgae, while a well-developed coral community extended the outer of farms to the reef crest over ~600 m-wide (Fig 6-middle). Along the control radial-3, benthic communities transitioned from

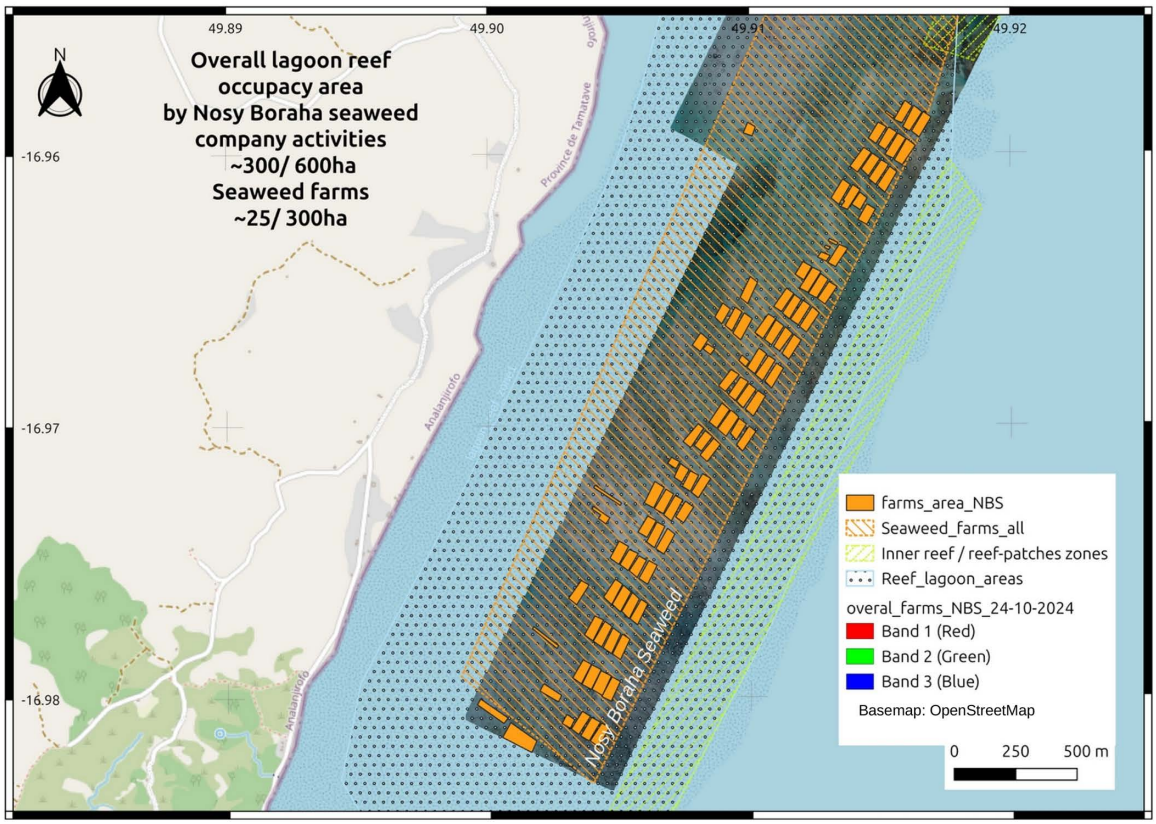


Fig 4. Lagoon reef occupancy by Nosy Boraha Seaweed company activities, based on a drone survey conducted on 24 October 2024. Seaweed activity zones are shown by orange dashed outlines. Farm layouts are represented by dark orange polygons (n = 92), with each farm consisting of six cultivation modules. The orthomosaic layer is a red–green–blue image. Base map data: OpenStreetMap contributors (https://www.openstreetmap.org), licensed under the Open Database License (ODbL) v1.0 (https://opendatacommons.org/licenses/odbl/1-0/).

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near-shore *Thalassia sp* meadows to sandy channel with dominated by *Halophila sp, at* mid-lagoon macroalgal zones (*Caulerpa sp* and *Hydroclathrus sp)* were observed. Corals patches near the reef crest were less diverse than on radial 2 and extended over400 m-wide (Fig 6-bottom).

2.2.5. Physico-chemical parameters. Discrete salinity sampling on the three radials in November 2024 yielded an average value of 34.43 ± 0.04, with slightly lower values along the control radial (radial 3) compared to radials 1 and 2 (Fig 7-a). Nutrient concentrations were low and characteristic of tropical environments (Fig 7-b,c,d). Along the three radials, the trend was toward a decrease in dissolved inorganic nitrogen (nitrates, nitrites, ammonium) and particularly phosphate concentrations with distance from the reef crest. Phosphates were completely depleted at stations 3A and 3B (control radial), the phenomenon being less pronounced on radial 2 and especially radial 1 (downstream of the seaweed cultivation plots). At the same time, chlorophyll-a concentrations appeared to be higher at stations 3A and 3B compared to the other stations (Fig 7-e).

2.3. Environmental law analyses

2.3.1. Recent implementation of a Marine Protected Area. Communities of Nosy Boraha are represented by through the Platform of consultation and support for the sustainable development of Sainte-Marie island (PCADDISM). Established in 2017 with the support from GRET, PCADDISM operates as a local association bringing together key

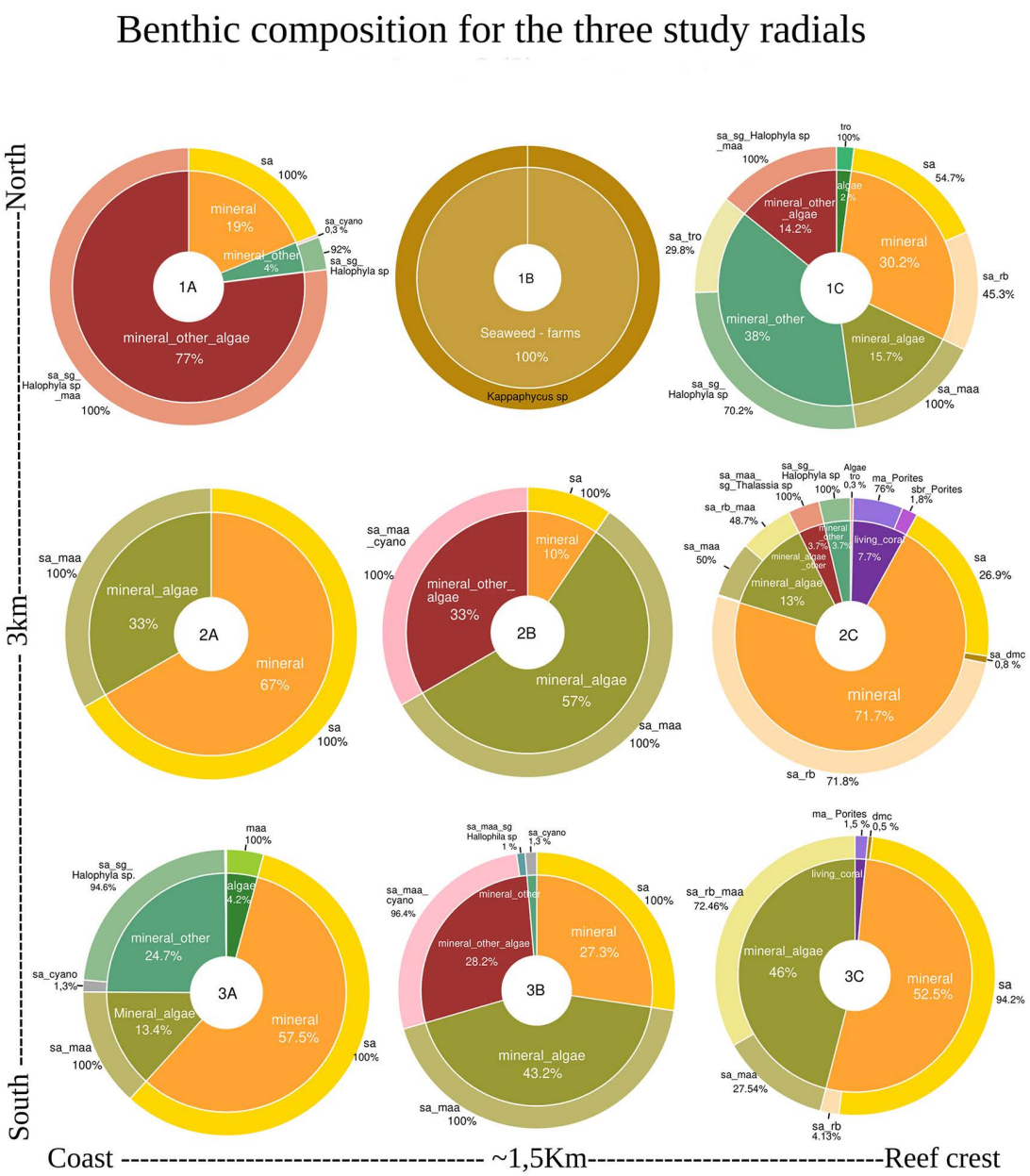


Fig 5. Ring charts representing abiotic and biotic benthic components along the shore-to-barrier reef gradient for the North (1), South (2) and Control (3) radials at each sampling point (A, B, C), following the Global Coral Reef Monitoring Network (GCRMN) protocol. Colours represent benthic categories. Major categories are shown in the inner rings and minor categories in the outer rings. Major categories: orange – mineral; olive green – mineral_algae; turquoise – mineral_other; scarlet – mineral_algae_other; brown – seaweed farms; dark green – algae; violet – living coral. Minor categories: golden – sand (sa); light beige – sand and coral rubble (sa_rb); dark brown – sand and dead massive coral (sa_dmc); light yellow-green – sand, macroalgae and rubble (sa_rb_maa); light olive green – sand and macroalgae (sa_maa); light turquoise – sand and seagrass (sa_sg_genus); pink – sand and macroalgae with cyanobacteria (sa_maa_cyano); light orange – sand, seagrass and macroalgae (sa_sg_maa); two shades of light violet – massive and small branching *Porites* sp. (ma or sbr). S3 Appendix, underwater photos of abiotic and biotic benthic categories.

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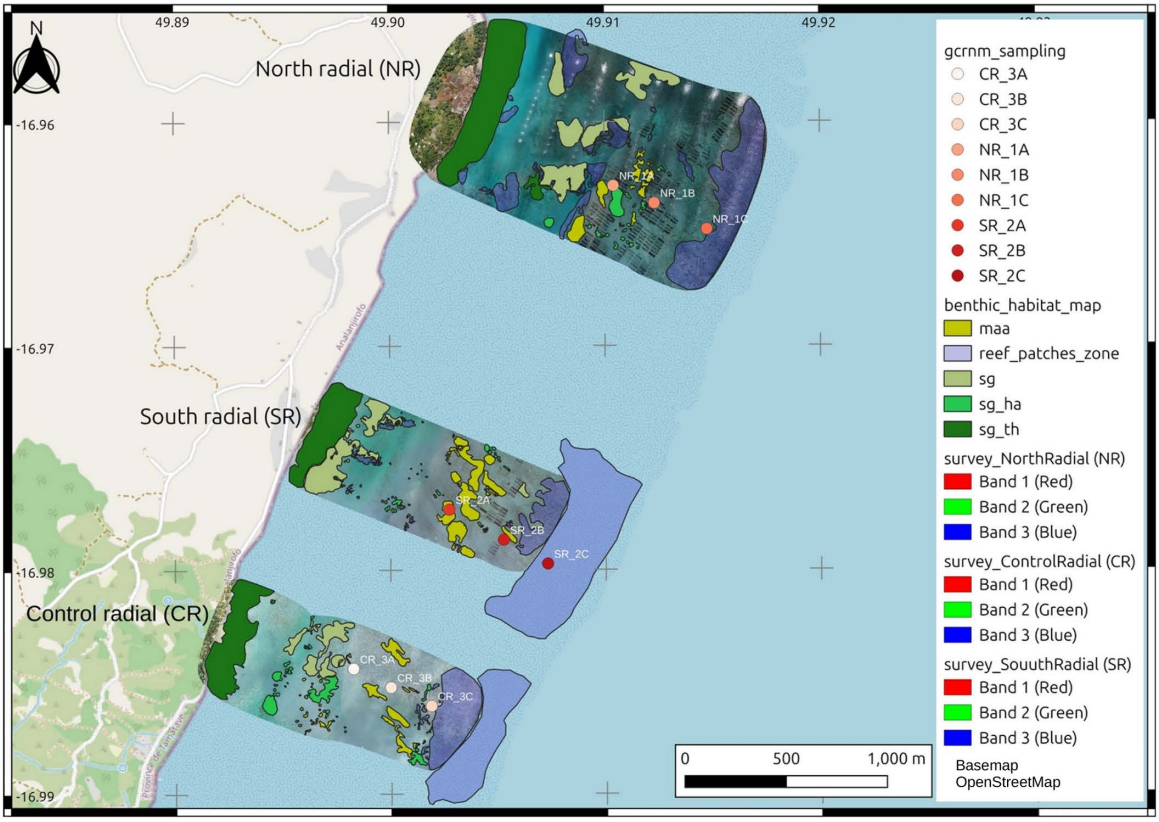


Fig 6. Habitat maps derived from drone surveys (area delineated by a black outline). Maps described the spatial distribution of biotic benthic communities for each radial: North radial (NR), South radial (SR) and Control radial (CR). Polygon colours indicate the main habitats identified: dark yellow – benthic macroalgae zones (maa); light green – seagrass sp. (sg); dark green – *Thalassia* sp. seagrass; apple green – *Halophila* sp. seagrass; dotted light violet zones correspond to reef patch areas. The orthomosaic layers are red–green–blue images. Base map data: OpenStreetMap contributors (https://www.openstreetmap.org), licensed under the Open Database License (ODbL) v1.0 (https://opendatacommons.org/licenses/odbl/1-0/).

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community stakeholders. Its objectives include the conservation of shared natural resources and the promotion of their sustainable use by the island's population. In 2020, PCADDSIM initiated the administrative process to establish Marine and Terrestrial Protected Area (AMTP) in Nosy Boraha, in collaboration with the Malagasy Ministry of Environment and Sustainable Development (GRET website, January 2025). This local initiative represents an unprecedented example of community-led conservation within Madagascar's national framework, while aligning with the principles of the MIHARI network locally managed marine areas (LMMA). The current AMTP development plan was developed through consultations with local and scientific stakeholders and validated by the Madagascar Protected Zones System committee. The official handover of the signed decree granting temporary protection status to the new 'Sorkay' Marine and Terrestrial Protected Area (AMTP) was celebrated on 5 February 2026. This celebration marks the culmination of an inclusive consultation process initiated in 2018 and finally provides a legal framework for the traditional rules already implemented by local communities (GRET post LikedIn: https://www.linkedin.com/posts/gret_tsarakobaby-sainte-marie-mise-en-protection-activity-7425174167563517952-xExR?utm_source=share&utm_medium=member_desktop&rcm=ACoAADNy3wkBqmufPkP3j22zjeCrTBBq_-w_jys. (visited on: 7/02/2026)). Delineation of seaweed activities will be updated in future versions, following their inclusion in the newly defined '*sustainable usage zone'* was recently proposed during the local and scientific consultation. At the national level, the expansion of seaweed production

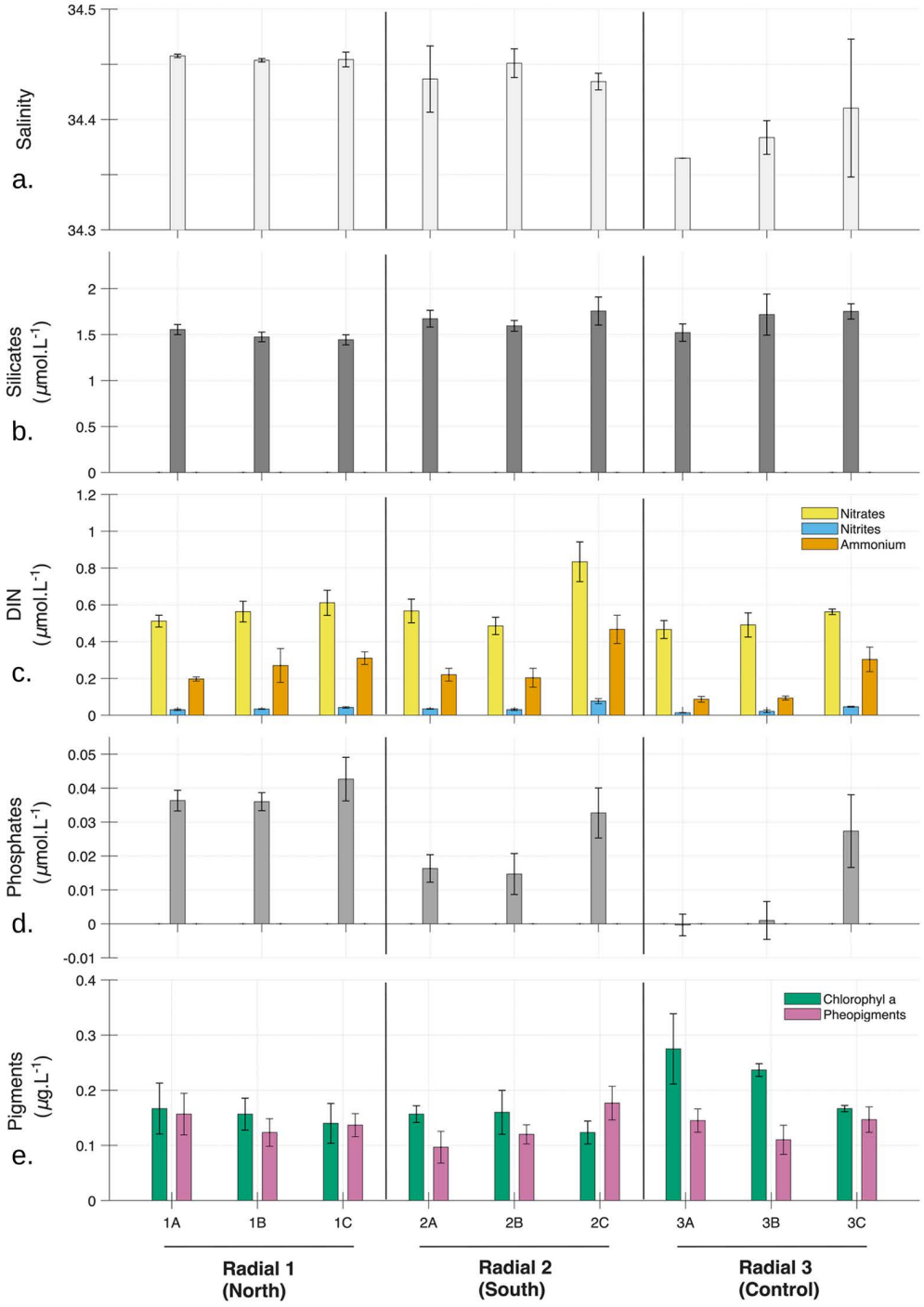


Fig 7. Physico-chemical parameters of the three radials: (a) Salinity; **(b)** Silicates; **(c)** Dissolved Inorganic Nitrogen (DIN) corresponding to nitrates, nitrites and ammonium; **(d)** Phosphates; **(e)** Pigments, replication n = 3.

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is guided by key policy documents, notably the National Plan for Integrated Coastal Zone Management (PNGIZC) and the Seaweed Development Plan (2021).

2.3.2. Law framework investigation. State law: short-list of the main provisions in the Malagasy Constitution (2010), legislation for environment, protected areas, marine protected areas and economic activities such as fisheries and aquaculture, Table 1**-I**. Customary code: definition of Dina, **Table 1-II** and Nosy Boraha Dina, **Table 1-III**.

3. Discussion

3.1. Three domains insights, trough social to ecological sciences

The ethnographic component of this study revealed both direct and indirect benefits of seaweed aquaculture for the inhabitants of Ilampy and neighbouring villages. Increased household income has enabled investment in housing and education, while creating new employment opportunities for women and thereby enhancing their economic autonomy. These findings are consistent with observations from the Nosy Ankao archipelago and the Atsimo Andrefana region [28]. However, evidence from Zanzibar suggests that seaweed farmers income may remain constrained by limited market access, empowerment challenges and operational difficulties [11]. Outcomes must therefore be examined on a case-by-case basis, taking into account the specific local context of each seaweed-producing area. Seaweed farming also involves physically demanding and repetitive labour under harsh environmental conditions (intense heat, sun exposure, sea salt

Table 1. State law and customary code.

I. State Law		
Law	**Text concerned**	**Description**
Law n° 90–033	Environmental Charter (1990)	Establishes the core principles of environmental protection, including public participation and sustainable development. It creates the National Environmental Office (ONE) and makes Environmental Impact Assessments mandatory for certain projects. It also promotes environmental awareness and education.
Law n° 2001–005	Protected area management code	Regulates the creation and management of protected areas in line with IUCN standards. It introduces community-based and collaborative management approaches and allows public and private actors to manage protected areas. The law emphasises ecological integrity and sustainable resource use.
Law n° 2015–003	Environmental code (updates the1990 law)	Integrates environmental governance and defines the roles of State, local authorities, and private actors. It establishes key principles such as precaution, prevention, and "polluter pays". The Code strengthens EIA and SEA systems and consolidates provisions on pollution, biodiversity, and climate change.
Law n° 2021–005	Marine Protected Areas - coastal areas	Focuses on the conservation of coastal and marine ecosystems through Marine Protected Areas. It supports marine spatial planning, sustainable tourism, and biodiversity protection. The law promotes community-based management and benefit-sharing to enhance climate resilience.
Law n° 2015–005	Fisheries and aquaculture code	Regulates fisheries and aquaculture through licensing, quotas, and conservation measures. It promotes sustainable use of aquatic ecosystems and community involvement while penalising illegal fishing. **Seaweed aquaculture is specifically governed by Decree No. 841/2024** of the Ministry of Fisheries and the Blue Economy, which sets out the terms and conditions for granting operating permits, as well as the rights and obligations of project promoters.
II. Customary Code/ Dina		
It can be defined as *a "*convention" or *a 'c*ollective and deliberate decision*"* [15]		
Each region has its own Dina and, in a general, the Dina must not be contrary to the State law. If the State law. Where State law is incomplete, a judge may refer to the Dina when delivering a judgement.		
III. Local Dina of Nosy Boraha		
The local Dina of Nosy Boraha applies to the entire territory as a complement to, or reinforcement of, formal State law. This local customary law is non-binding, aims to resolve conflicts trough fairness and balance in order to safeguard peace and social harmony, In accordance with the *Fihavanana* principle.		
Fady (taboo) established by the local population also contribute to biodiversity conservations, for example:		
• A ban on fishing for the whales (*zanary* be) and guitar ray (*sorokay).*		
• A ban on human presence in sacred sites classified within Marine Protected Area as i*ntegral protection zones* (strict nature reserves).		

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and strong odours), comparable to other aquaculture sectors such as oyster and shrimp farming. Although the company Nosy Boraha Seaweed has introduced measures to improve working conditions (e.g., provision of kayaks, shaded areas and adaptations at the processing site), long-term and comparative studies involving both participating and non-participating villages are needed to assess fully the socio-economic and cultural impacts. Beyond explicitly articulated narratives, this study also highlights the significance of silences and unspoken issues within seaweed aquaculture discourses. As argued by. Marco Furrasola (2023) [31] silence constitutes a social practice in its own right, shaped by power relations and specific contexts of enunciation. Attending to these silences enables a more nuanced understanding of marine socio-ecosystems and raises critical questions about the limits of participatory governance and the conditions under which interdisciplinary knowledge is produced within nature-based solutions frameworks.

From an ecological perspective, seagrass and macroalgal zones were the dominant habitats co-occurring with seaweed farming activities within the lagoon. As noted by Spillias et al. (2023) [17], the large-scale and long-term effects of seaweed farming on seagrass ecosystems remain poorly documented, underscoring the need for extended monitoring. While *Kappaphycus* cultivation plots take up dissolved inorganic nitrogen and phosphates from the water column (Fig 3), similarly low nutrient concentrations were recorded in natural communities at the control sites, particularly downstream of the reef crest (< 1 μM for dissolved inorganic nitrogen and < 0.04 μM for phosphates). Based on our survey conducted in November 2024, the presence of seaweed farms therefore appears to cause only limited, if any, changes in the physico-chemical conditions of the reef. However, the potential impact of *Kappaphycus* farms on the release or uptake of dissolved organic matter remains to be determined. In November 2024, chlorophyll-a concentrations were higher at stations 3A and 3B along the control transect than at stations located within seaweed fields or downstream, possibly indicating higher phytoplankton production in natural seabed areas. Although this may partly explain the phosphate depletion observed at these stations, multiple interacting or confounding factors (e.g., terrigenous nutrient inputs or current dynamics) may also be involved. Further studies are required to clarify these trends and to confirm whether *Kappaphycus* farming has no, or only limited, impact on nutrient cycling and planktonic communities within the lagoon of Nosy Boraha. We strongly recommend investigating the potential release of organic matter by farmed *Kappaphycus alvarezii*, as this may affect microbial loops in both the water column and sediments. The presence of cyanobacterial mats within seagrass and macroalgal habitats raises concerns regarding eutrophication and cumulative anthropogenic pressures. Known drivers include warm and calm waters, high light availability, nutrient enrichment and reduced grazing pressure [32]. Potential local contributors include overfishing, destructive fishing practices, anchoring, trampling and increased nutrient or iron inputs. Disentangling these drivers will require seasonal surveys and long-term ecological monitoring. Such research would also improve understanding of episodic biological disturbances reported by farmers, including green tides (algal bloom episodes), epiphytic filamentous algae (EFA) proliferation and bacterial diseases such as ice-ice [33–35]. Notably, green tides are perceived locally as highly disruptive, underlining the importance of integrating ecological observations with local knowledge and interpretations. Regarding invasion risks, there is currently no evidence of *Kappaphycus sp.* invasion associated with seaweed farming in Madagascar (personal observations; personal communication with the NBS director). However, this apparent absence of impact may reflect limited monitoring capacity [10].

Governance and natural resource management constitute a third, closely interconnected domain shaping seaweed aquaculture outcomes. Over the past decade, the population of Nosy Boraha, supported by the NGO GRET through the 'Tsarakobaby' project (phases 1 and 2) under the 'Commons and Shared Governance Programme' of the French Development Agency, has actively promoted the establishment of a Marine and Terrestrial Protected Area. Aubert (2024) [14] documented strong local involvement in the use, regulation and protection of natural resources, a finding corroborated by testimonies from Ilampy inhabitants and AVA association members in the present study. Previous research similarly highlights strong local engagement in coastal protection and marine resource management [34,36], grounded in communal organisation and the articulation of Dina with national law. These findings support the arguments of Shackeroff et al. (2007) [35] and insights from Gentiluchi & Stoica (2024) [37] which suggest the resource management policies and

environmental strategies are most effective when traditional knowledge and local populations are meaningfully integrated. In parallel, private seaweed farming actors, including Nosy Boraha Seaweed and Solvalg, have contributed to marine and land-use planning efforts aimed at organising activities, limiting environmental impacts and reducing potential spatial conflicts.

3.2. Interdisciplinary reflections, towards sustainable development goals

The coexistence of scientific and local knowledge highlights a plurality of ecological rationalities: seaweed diseases, green algal bloom episodes and other environmental disturbances are not only biological phenomena, but also socially interpreted occurrences, codified through customary rules and revealing tensions between local temporalities and standardised scientific frameworks. Overall, this baseline study underscores the importance of a synergistic nature-based approach that integrates seaweed farming with small-scale fisheries and diversified marine production systems [7,38]. The concepts of marine permaculture and 'Satoumi' [39,40], offer a promising framework for productive seascapes capable of delivering positive ecological and social outcomes. Such an approach requires engagement across multiple disciplines, as well as the diversification of activities and markets. However, achieving these outcomes also demands close attention to underlying economic structures [7, 41]. At present, much of the added value within the Cottonii seaweed value chain accrues outside producer countries [42]. A more equitable distribution of value, supported by adapted legal frameworks and strengthened local governance mechanisms, is therefore essential. In this context, local Dina conventions in Nosy Boraha may play a key role in reconciling environmental conservation with long-term social and economic development [14,15, 43]. From a blue justice perspective, it is imperative to establish long-term socio-ecological programmes that critically assess how ecological, economic and social benefits, constraints and risks are unevenly distributed among different actors. While sustainability and nature-based solutions frameworks often prioritise measurable economic or ecological outcomes, they may overlook lived experiences of labour, power asymmetries between institutions, NGOs, private companies and local communities, as well as internal social differentiations related to gender, age and status [44,45].

The lexical analysis of the academic corpus on interdisciplinarity reveals a predominance of more abstract and normative concepts:*ecosystem, management, governance, development, ecological, study, knowledges*, reflecting the conventions of scientific writing and interdisciplinary research (Fig 8). This shift highlights the distance between lived experiences and their analytical translation, and points to the effects of genre and the epistemic priorities inherent in nature-based solutions and blue economy frameworks.

4. Conclusions

The combined anthropological, ecological, and legal findings reveal that potential conflicts over: (i) marine spatial planning and (ii) seasonal disruptions such as green algae blooms are best addressed through integrated interdisciplinary approach. Ethnographic results show social cohesion rooted in *Fihavana* principle between seaweed farmers, fishers, companies, and other users. Ecological data highlight spatial location of seaweed farming areas, and natural habitats: seagrass meadows, macroalgae zones, and reef habitats, as well as potential seasonal productivity losses linked to green algal bloom (green tide), underscoring the need for adaptive, ecologically informed zoning. Legal analyses demonstrate that the emerging Marine and Terrestrial Protected Area framework and national coastal policies offer institutional tools to formalize such zoning while recognizing customary codes. Together, these domains suggest that conflicts are not merely spatial but temporal, shaped by seasonal ecological variability and livelihood dependencies. Interdisciplinary integration enables the alignment of customary norms with scientific monitoring and legal planning instruments. This alignment can support dynamic marine spatial planning that accommodates seasonal farm relocation, ecosystem protection, and livelihood continuity. By embedding ecological thresholds into socially legitimate governance structures, conflicts can be anticipated rather than reacted to. Ultimately, resolving spatial and seasonal tensions requires co-management approaches



Fig 8. Interdisciplinarity integration, in word-cloud visualization, of social end ecological insights of this investigation. Lexical analysis for academic discussion corpus. Font sizes are proportional to term frequency.

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that integrate local knowledge, ecological evidence, and legal authority and Dina, which could already provide culturally legitimate mechanisms for conflict resolution between seaweed farmers, fishers, companies, and other users.

Our investigations provide a first assessment of the sustainability of seaweed aquaculture on Nosy Boraha and its interactions with local communities and the natural environment. Our socio-ecological study identifies several challenges that need to be addressed. Key priorities include upgrading drying and storage infrastructure, revising quotas, mitigating seasonal and climatic constraints, and strengthening the legal and ecological monitoring frameworks for lagoon and coastal zones. Sustained collaboration among private operators, local authorities, and community organisations is essential to maximise the benefits of seaweed farming while minimising environmental and social risks. Mapping ecological, social, and economic processes is a critical step towards effective marine spatial planning. This study contributes detailed cartography of seaweed farming areas and associated natural habitats, which will be shared with environmental managers and local partners to support future decision-making. While the study highlights the socio-ecological and governance benefits of seaweed aquaculture, it also calls for complementary ecological studies and a deeper examination of the power relations and inequalities that may shape these dynamics.

Overall, our findings demonstrates that, when carefully managed and locally integrated, seaweed farming represents a promising model for sustainable blue economy development in Madagascar and the Western Indian Ocean.

5. Materials & methods

5.1. Study site and seaweed farming system

Nosy Boraha (Sainte-Marie Island) is located off the north-eastern coast of Madagascar and belongs to Analanjirofo Region (Fig 9). The island covers approximately 245 km² and has a population of about 30,282 inhabitants (~120 inhabitants/km²). It is administratively divided into four districts that comprising 17 villages (fokontany). The main economic activities includes tourism, fishing, seaweed farming, and agriculture. The island hosts a diversity of marine ecosystems,

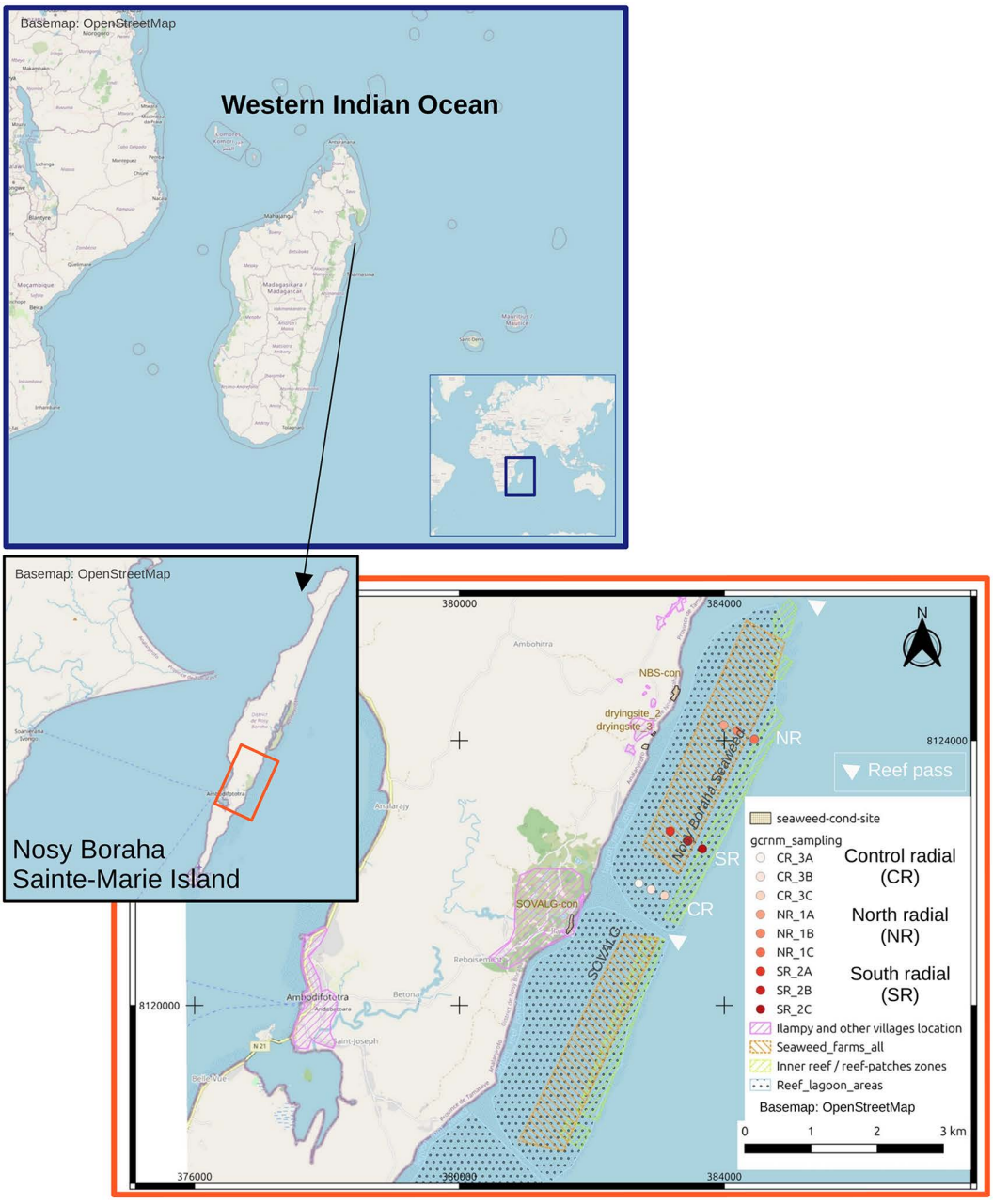


Fig 9. Interdisciplinary study sites. Seaweed aquaculture areas are indicated by dashed orange lines for Nosy Boraha Seaweed (lagoon reef area north) and Société de Valorisation des Algues (lagoon reef area at the south of NBS). The barrier reef is marked with dashed green lines. The three shore-to-reef radials (North 1, South 2 and Control 3) were used to characterise the northern lagoon at three sampling points (A-C) along each radial, the red colour gradation of the points represents the geographical gradient from north to south and reflects the cross-shelf transition from the coastline to the barrier reef for each radial. Villages involved in ethnographic surveys and environmental law studies are indicated by dashed light violet lines: Ilampy (east coast), Ambodifotatra (west coast), and Ankobaoba (east coast), Nosy Boraha, Madagascar (Western Indian Ocean). Base map data: OpenStreetMap contributors (https://www.openstreetmap.org), licensed under the Open Database License (ODbL) v1.0 (https://opendatacommons.org/licenses/odbl/1-0/).

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including mangroves, seagrass, rocky shores, and coral reefs. Along the eastern coast, a lagoon approximately 15km long extends from Île aux Nattes in the south to the Ampanihy Peninsula and mangrove forest in the north,covering an area of about 2,400 ha. The lagoon is bounded by a barrier reef located on average at 1.5 km, based on offshore GIS measurements derived from remote sensing imagery. Lagoon depth ranges from 1.5 m and 5 m, with tidal amplitudes between 0.5 m and 1.5 m.

The lagoon area used for NBS seaweed farming is delimited by two reef passes that allow flow circulation with oceanic waters. Farming activities are concentrated in very-shallow waters (0.50-2 m depth) on the lagoon reef area (Fig 9). The most recent coral reef monitoring program focused on outer reef slop and reported a stable coral cover in the north >45% (station îlot Boeny). In contrast, southern stations (Lakana and île aux Nattes) exhibited several coral degradation, with coral cover below <10% and extensive macroalgae colonisation [46]. Earlier surveys reported an overall mean coral cover approximately 35% [47], suggesting a decline potentially linked to anthropogenic pressures and/or natural disturbance, fringing reefs along the eastern having 'low ecological interest' [36]. But, to date inner reefs and lagoonal habitats have not been specifically investigated.

The Asiatic haplotype *of Kappaphycus alvarezii* (Cottonii) was introduced into the Western Indian Ocean in the late 1980s and subsequently established in Madagascar due to its high growth rate (4–12% day^{-1}) and the low cost and simplify of cultivation techniques [28,42,48]. Three seaweed farming companies currently operates on Nosy Boraha: Nosy Boraha Seaweed (NBS), Société de Valorisation des Algues (Sovalg), and Madalgue. Theses companies collaborate with 238 local seaweed farmers operating under an entrepreneurial status, each managing around 0.3 ha of farming area. Individual production ranges from 5 to 15 tonnes of fresh seaweed per month, equivalent to 0.5-1.5 tonnes of dry biomass, corresponding to an annual production of 6–18 tonnes of dry seaweed per farmer. In addition to production, theses companies play a central role in structuring the local seaweed farming sector, employing approximately 129 permanent staff and 200–350 seasonal or daily workers.

Seaweed farming by NBS and Sovalg relies on the off-bottom cultivation method, which is well suited to very shallow lagoonal environments. NBS farming activities are concentrated in the northern part of the lagoon, where 145 farms are deployed (Fig 9). Each farm comprises six cultivation plots, each containing 100 cultivation lines, subdivided into four compartments of 25 lines. Lines are 11 m long and stocked 100 g of *K. alvarezii* cuttings. Yield is expressed as harvested biomass per plot (in tonnes). Farms are managed individually, whit one module planted per week (100 lines). A production cycle (planting - harvest) lasts approximately 45 days, allowing about seven cycles per year.

5.2. Interdisciplinary study

The approach combined anthropology, marine ecology and environmental law, defining sustainability as the capacity of seaweed farming to improve local livelihoods while maintaining or enhancing ecosystem conservation. Geomatic tools were used to design the sampling strategy and to locate the main east coast villages involved in the activity (Fig 9). Team composition, stakeholders engagement and integration of findings were identified as key components of the approach. Regular coordination meetings were held to align objectives and terminology, share relevant literature and develop the methodological framework (Table 2).

An interdisciplinary exploratory lexical analysis was conducted and visualised on word clouds. This was applied to two distinct corpora: (i) ethnographic materials derived from interviews and field observations, and (ii) the discussion section of this article. Prior to analysis, the texts were normalised and filtered to remove stop words, grammatical connectors, and verb forms, retaining only meaning-bearing lexical items (primarily nouns and descriptors). Word frequencies were then computed and visualised using word clouds, with font size proportional to term frequency. This approach does not aim to provide a comprehensive linguistic analysis nor to establish an objective hierarchy of issues, but rather to make visible the frames of meaning through which seaweed aquaculture is articulated, experienced, and discussed by both local actors and researchers. All activities were conducted in accordance with Malagasy cultural, socio-economic and institutional contexts.

Table 2. Overview of methodologies used in interdisciplinary, anthropological, ecological, and environmental law studies.

Interdisciplinary approach		
• **Team composition:** the research team included specialists in anthropology, environmental law, chemistry, marine biology,and coral reef ecology. Team members jointly selected and co-supervised the Master's students (three master students one for each domain). All students were Malagasy, facilitating communication with local communities and authorities (Fig 1e).		
• **Stakeholder engagement:** the collaborations were conducted through two meetings held at Nosy Boraha: a project kick-off meeting in May 2024 and a progress and preliminary results meeting in November 2024 (Fig 1f). Participants included project partners, local and national authorities - Ministries of Fisheries, Blue Economy and Environment, and representatives of local communities, including the local fisheries committee, the chiefs of the 17 villages (fokontany), and members of the Platform for Consultation and Support for the Sustainable Development of Sainte-Marie Island (PCADDISM).		
• **Integration of findings:** On-site seminars and discussions facilitated knowledge exchange, incorporation of local expectations into study design, and coordination of result dissemination, with attention to potential conflicts.		
Interdisciplinary interpretation of findings: exploratory lexical analysis visualised on word clouds.		
Anthropology	**Ecology**	**Environmental law**
communities perceptions of seaweed farming	benthic composition, environmental conditions and spatial occupancy of seaweed farming	governmental legal framework and customary codes
Bibliographic review	Bibliographic review: ecological studies of potential impacts benefits of seaweed farming in lagoon reefs.	Bibliographic review.
Qualitative approach	Physical and chemical parameters:	Qualitative approach
Ethnographic survey:	• Drifter tracks, to describe current direction.	Legal framework:
• Participant and floating observation [49].	• Temperature and salinity.	• environmental legislation.
• Fourth months immersion.	• Nutrient concentrations and pigment concentrations.	• customary codes, Dina.
• Semi-structured and open interviews.	Benthic components description and mapping:	Field campaign, surveys to:
• Discourse analysis using a thick description approach [50].	• Benthic underwater surveys LIT (Line Intercept Transect) following the Global Coral Reef Monitoring Network protocol.	• Investigate the specific Dina of Nosy Boraha.
Quantitative analysis		
• Interpretative analysis by lexical frequencyanalysis in word cloud representation [51,52].	• Mapping: UAS/ drone surveys for habitat maps and seaweed activities occupancy. Ecological description of study radials (north, south control).	• Understand the insights concerning the Marine Spatial Planning project and the trajectory of the Terrestrial and Marine Protected Area creation.

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5.3. Ethical statement

Prior to participation, all individuals received a clear explanation of the study objectives, procedures, expected benefits, and their rights, including the right to withdraw at any time without consequences. This information was provided during an initial briefing meeting and field campaigns, a verbal informed consent was obtained from all participants before their inclusion in the study.

The study was conducted in accordance with the American Anthropological Association (AAA) Statement on Ethics, adhering to core principles of ethical and methodological best practice, including: doing no harm, transparency and honesty in research activities, obtaining informed consent and necessary permissions, balancing ethical obligations to collaborators and affected parties, ensuring accessibility of research results, maintain respectful and ethical professional relationships protecting and preserving research records, please see fully definition in: American Anthropology Association Statement on Ethics https://americananthro.org/about/policies/statement-on-ethics/.

In addition, explicit permission was obtained from all individuals prior to photographing, audio recording or conducting interviews. All participants approved the publication of images and recordings included in this study.

5.4. Anthropological study

The ethnographic data for this study were collected over eight months (May to December 2024). We apply a qualitative study case in the main seaweed village farmer of Nosy Boraha. First phase consist in the review of tropical seaweed farming studies in the Western Indian Ocean region and specially in Madagascar, archives, decrees, laws, and other unpublished data 'grey literature, (unpublished literature & institutional documents (non exhaustive list): Plan de Développement de l'Algoculture- Ministry of Agriculture, livestock and fisheries of Madagascar (MAEP), 2021; Report: A. T., Tatangirafeno, S., Rakotonjanahary, F., Tsiresy, G., Mara, E. R., Eeckhaut, I., & Lavitra, T. (2016). Inventaire et étude de faisabilité de sites propices à l'algoculture, l'holothuriculture, la gestion de l'exploitation de poulpes et de crabes dans la Région Atsimo Andrefana; Rapport d'étude, MHSA – PRU (Contrat n° 166/C/PIC2/2016), 357 p; Report: Inventaire et étude de faisabilité des sites propices à l'algoculture dans la région d'Atsimo-Andrefana. Mentionné pour l'équilibre entre régulations coutumières et modernes dans l'accès aux ressources marines, ainsi que pour les recommandations sur la cogestion participative (2020) pp. 3–12). The second phase consisted if in semi-structure interviews, participative and floating observation [49] and discourse analysis using a thick description approach [50]. At the out-set of the study, the research team conducted courtesy visits to villages involved in seaweed aquaculture (Ambodivoanio, Ambodiforaha, Ankobahoba and Ilampy), as well as seaweed processing sites for two companies, Sovalg (Ilampy) and Nosy Boraha Seaweed (Ankobahoba) (Fig 1c, d). These visits aimed to introduce the study, contextualise local practices, and identify where seaweed farmers primarily reside (Fig 1b-d). Based on these visits, Ilampy was selected as the main study site. Then, the Master's student in Anthropology and the Postdoctoral researcher conducted participant observations and semi-structured interviews with seaweed farmers, stakeholders, company managers and community representatives, in both the local Malagasy dialect spoken on Sainte-Marie Island and French. To deepen the study and better understand the social dynamics linked to the seaweed activity (e.g., labour distribution, gender issues, and daily routines), the Master's student lived during fourth months with a woman seaweed farmer who lives with her daughter. 'Tatie Andrea's' house is located in Ilampy, near the seaweed conditioning site, allowing convenient access. This immersion allowed the researcher to deeply experience de all-day life, establish relationships with both seaweed farmers and activity managers. All personal and place names are real and were approved by participants for publication (see Ethical Statement).

To complement the data collected, a lexical frequency analysis was conducted on interviews (S1 Appendix) and the anthropological results corpus to identify salient concepts in participants' perceptions of seaweed farming and visualised in word-cloud representation following the procedure principles from qualitative content analysis and lexical ethnography (Fig 2) [51,52].

5.5. Ecological study

5.5.1. Abiotic and biotic benthic components. Three shore-to-barrier reef radials were chosen within the study area (Fig 9): one located in the northern part of NBS exploitation zone (North radial, R1), one in the southern part of the NBS zone (South radial, R2), and one control radial located south of the NBS exploitation area where no seaweed farming occurs (Control radial, R3). Along each radial, three sampling stations (A, B, and C) were established within the lagoon. For the North and South radials, station A was located downstream of the seaweed farms, station B within the farming area, and station C upstream of the farms, closest to the reef crest. The control radial followed the same spatial configuration. Benthic communities along each shore-to-barrier reef transect were assessed using underwater visual censuses following the Line Intercept Transect (LIT) method, in accordance with the Global Coral Reef Monitoring Network protocol [67]. At each sampling station (A, B, and C), three 20 m transects were surveyed, resulting in a total of 27 transects across the study area. Benthic composition was classified into four major biotic and abiotic categories: unconsolidated substrate (sand), live coral, algae, and other benthic components. Additional minor categories were assigned based on the dominant benthic organism present (S4 Appendix). When possible, organisms were identified to genera level (S5 Appendix).

5.5.2. Aerial surveys and habitat maps. Aerial photogrammetric surveys were conducted using uncrewed aerial system (UASs, drone) equipped with RGB sensor (DJI Phantom 4 and DJI Mavic 3), image processing and orthomosaic reconstruction were performed using Agisoft Metashape (v.2.1.2) following the flight and photogrammetric processing parameters described by Urbina-Barreto et al. (2026) [53]. Geographic Information System (GIS) analyses were carried out in QGIS (v. 3.26.3) to define sampling locations, describe the spatial distribution of benthic habitats, characterise current orientation, and quantify the spatial extent of seaweed-farming activities (surface occupancy). Habitat and farming areas were manually delineated as polygons from the orthomosaics. The surface area of each polygon was calculated by GIS command and aggregated to estimate total habitat coverage and the lagoon area occupied by NBS seaweed-farming activities. Habitat maps derived from orthomosaics were validated with field observations, underwater photos/videos, and underwater benthic surveys (LIT).

5.5.3. Physico-chemical parameters. Temperature and salinity were measured in the northern lagoon (near point 1c, Figs 3, 9) in July 2024 (winter) and November 2024 (summer) using Aquabox (monthly continue register – NBS systems) and RBR concerto multi parameter sensors (7 days continue register). Hydrodynamic conditions were assessed using surface drifter deployments conducted at high tide near the reef crest, as seawater circulation is primarily driven by incident ocean waves [54]. Drifters consisted of a custom-built system equipped with a portable GPS (Garmin GPSMAP 86i). Each deployment lasted approximately 45 minutes.

At each station along all radials, seawater samples were collected in triplicate (n = 3) at low tide and one hour before and after. Samples were used to determine nutrient concentrations (i.e., nitrate, nitrite, ammonium, phosphate, and silicate), pigment concentrations (chlorophyll *a* and pheopigments), and salinity. Samples for nutrient analyses were filtered either through Millex-HA cellulose ester filters (for silicate analysis) or GF/F glass fibre filters (Whatman) for all other nutrients. Filtered samples were stored in 125 mL Nalgene bottles, or 100 mL Schott bottles for ammonium, kept cool during transport, and subsequently stored at −18°C until analysis, except for silicate samples, which were stored at 4°C. Ammonium concentrations were determined using the manual colorimetric method described by Aminot A (1983) [55], with absorbance measured in 10 cm path-length cuvettes using a UV-1900 spectrophotometer (Shimadzu). Other nutrients were analysed using an AutoAnalyser III (Seal Analytical) following the methods of Treguer and Le Corre (1975) [56], with modifications for phosphate and silicate analysis as described by Aminot and Kerouel (2007) [57]. For pigment analyses, 1 L of seawater was filtered through a 47 mm Whatman GF/F filter (for al other nutrients), and filters were stored at −80°C until analysis. Pigments were extracted in 90% acetone and quantified using a Trilogy fluorimeter (Turner Designs), following protocols recommended by the SOMLIT observation network. Salinity was measured using a Guildline Autosal (OSIL) salinometer. As replication per station was limited (n = 3), no statistical analysis was performed. The reported results therefore represent a point-in-time observations in November 2024.

5.6. Environmental law study

The analysis of the governmental and customary legal framework was primarily based on a review of legal texts, institutional reports, and relevant scientific and grey literature, complemented by online sources and field observations. Particular attention was given to the interaction between national legislation and local customary code (Dina), and to how these regulatory systems are applied within local communities to reconcile the development of blue-economy activities with ecosystem conservation at Nosy Boraha.

Data collection was conducted in close collaboration with agents from Groupe de Recherche et d'Échanges Technologiques (GRET) and the Platform of Consultation and Support for the Sustainable Development of Sainte-Marie Island (PCADDISM). GRET staff provided expert testimonies and access to archival materials relevant to local governance and environmental management (GRET post LikedIn: https://www.linkedin.com/posts/gret_tsarakobaby-sainte-marie-mise-en-protection-activity-7425174167563517952-xExR?utm_source=share&utm_medium=member_desktop&rcm=ACoAADNy3wkBqmufPkP3j22zjeCrTBBq_-w_jys. (visited on: 7/02/2026)).

Customary laws (Dina) were investigated through a series of meetings and semi-structured interviews with the local population, members of PCADDISM, fishing committee, AVA association, and seaweed workers and coordinators team on conditioning sites. These exchanges provided insights into the role of Dina in marine resource governance, including rules governing the protection of marine areas and the authorisation of economic activities such as seaweed farming and fishing.

Supporting information

S1 Appendix. Interviews/quotations of ethnographic study.
(PDF)

S2 Appendix. Most frequent concepts identified in the interviews, words frequencies.
(PDF)

S3 Appendix. Habitat categories photos.
(PDF)

S4 Appendix. Abiotic and biotic benthic components, major and minor categories for benthic communities surveys.
(PDF)

S5 Appendix. Genius of minor benthic categories.
(PDF)

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