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Nation-wide hierarchical and spatially-explicit framework to characterize seagrass meadows in New-Caledonia, and its potential application to the Indo-Pacific

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Abstract :

Despite their ecological role and multiple contributions to human societies, the distribution of Indo-Pacific seagrasses remains poorly known in many places. Herein, we outline a hierarchical spatially-explicit assessment framework to derive nation-wide synoptic knowledge of the distribution of seagrass species and communities. We applied the framework to New Caledonia (southwest Pacific Ocean) and its 36,200 km2 of reefs and lagoons. The framework is primarily field-based but can leverage various habitat maps derived from remote sensing. Field data collection can be stratified by map products and retrospectively contribute to developing new seagrass distribution maps. Airborne and satellite remote sensing alone do not allow for the spatial generalisation of the finest attributes (species distribution and types of seagrass beds), but staged stratified field sampling provides synoptic views of these attributes. Using three examples, we discuss how the hierarchical and spatial information generated from this framework's application can inform conservation and management objectives.

Keywords : Coral reefs, Lagoon, Habitat mapping, Remote sensing, Dugong, UNESCO, Landsat

1. Introduction

Globally, seagrass beds are important ecosystems covering between 160,000 km^2 and 267,000 km^2 across 163 countries (McKenzie et al., 2020). Seagrass are marine flowering plants that can form extensive meadows (McKenzie et al., 2020) in relatively shallow waters (from intertidal down to ~60 meters). In several countries where they are abundant, seagrass meadows (or beds) contribute important ecosystem services and sustain the quality of life of coastal populations (Cullen-Unsworth et al. 2014, Unsworth et al., 2019). This contribution is particularly critical throughout the tropical realm (Cullen-Unsworth and Unsworth, 2013; McKenzie et al., 2021a, b; Waycott et al. 2011, Unsworth et al., 2018, Brodie et al. 2020). For instance, in the Pacific Island Countries and Territories (PICTs), McKenzie et al. (2021a,b) recently reviewed the information currently available regarding of seagrass species presence, as well as seagrass meadows' contributions to people's quality of life as a source of food and livelihoods and in terms of functioning and engineering of the broader mosaic of coastal ecosystems (Gacia et al. 2003, Lamb et al. 2017). Seagrasses form important habitats used by a myriad of organisms at various stages of their life cycles. Examples include charismatic species, such as the dugong (*Dugong dugon*) and green sea turtle (*Chelonia mydas*), which have strong cultural value for local communities (Marsh et al. 2011; Read et al. 2015; Sabinot and Bernard, 2016). Seagrass meadows are important yet increasingly under threats due to coastal and watershed developments, pollution, fisheries overexploitation, and physical stress. These social and ecological roles have supported the recurring emphasis put on seagrass in conservation agendas (Unsworth and Cullen 2010).

Considering their importance and conservation priority, seagrass beds are targeted by multiple monitoring and research programs, such as the SeagrassNet or SeagrassWatch programs (Duffy et al. 2019). These activities provide structural and ecological qualitative as well as quantitative data, with species check-lists associated with their cover, canopy height, biomass, etc. However, these efforts tend to be unequally distributed, both across and within countries. Overall, little is known consistently across the Indo-Pacific region, especially in large remote archipelagic areas that can be difficult and costly to access. For their review, McKenzie et al. (2021a) collated key data and information on species distribution for all PICTs. Part of this information came from selected specimens conserved in museums and herbariums that provided unquestionable national references and can still be consulted if needed. In the case of New Caledonia, however, the information preserved in museums is only the tip of the iceberg in terms of available knowledge on seagrass, since several research projects have investigated seagrass communities over the past 40 years. Research in the 1980s focused more on the primary production and benthic assemblages of some seagrass beds in the Southwest lagoon (Garrigue 1995). Since 2004, seagrass research in New Caledonia has been part and parcel of habitat mapping projects, some specific to seagrass, and some more inclusive of the wider reef and lagoon ecosystems. The recent reviews by

McKenzie et al. (2021a,b) at the Oceania scale, prompted us to pursue a synthesis effort, with a New Caledonia focus and a compilation of all available datasets, spanning years 1984 to 2017.

Because most shallow data were collected gradually as part of habitat mapping initiatives starting in 2004, we here first formalize a nation-wide hierarchical spatially-explicit framework based on *in situ* inventories and remote sensing-derived habitat maps. This framework promotes 1) the provision of species distribution maps for sub-areas as well as for the entire New Caledonia, 2) the definition and enrichment of a typology of seagrass communities with *in situ* inventories, 3) the development of detailed benthic maps of seagrass communities for sub-areas, 4) the mapping of seagrass beds (generically) for the entire targeted area, and 5) the mutual optimization of inventories and habitat mapping, through stratification of *in situ* surveys and spatial generalization. This framework can be applied to other areas in the Indo-Pacific region to plan for a consistent and as exhaustive as possible assessment of seagrass beds at national and archipelagic-scale. The framework's implementation may be adapted to the diverse contexts encountered across Indo-Pacific countries where mapping capacities may be limited or available remotely-sensed data not suitable to seagrass studies. However, field work is mandatory to design accurate and informative remote sensing product and lend credence in their application for decision making.

Herein, we aim to 1) briefly outline historical sampling and data collection efforts for New Caledonia, from which a multi-scale framework can be formalized, 2) describe generically the framework, the applicable scales, the inventory and mapping products that can arise from its implementation and the different links between these elements, 3) describe the application of the framework to all of New Caledonia's coastal waters, thereby complementing and expanding upon data provided in McKenzie et al. (2021a,b), and, finally, 4) discuss how data generated from the framework can support research, conservation, and management, with a focus on mega-fauna ecology, sea cucumber fisheries, and an assessment of the representation of seagrass beds in conservation areas.

2. Methods

2.1. New Caledonia study area and historical sampling

New Caledonia is a ~270,000-inhabitant French *sui generis* territory situated in the Western Pacific with a large political autonomy (Payri et al. 2019) that is exerted through three separate Provinces (Islands, North and South) and a central government. Local industries include most importantly mining, which entails a serious environmental cost, followed by fisheries, and some tourism driven by significant natural assets. The archipelago consists of a main continental island, Grande Terre (16,372 km^2), surrounded by a lagoon bordered by a 1600-km-long barrier reef. Numerous islands, atolls, and reefs of various sizes are located inside the Exclusive Economic Zone (Fig. 1). New Caledonia boasts a wide diversity of coral reef and lagoonal geomorphological features (Andréfouët et al. 2009) that are protected by 35 coastal marine protected areas and by the Natural Park of the Coral Sea (Parc naturel de la mer de Corail) (Gairin and Andréfouët 2020). Since 2008, six 'clusters' around Grande Terre, Isle of Pines, Entrecasteaux atolls, and Ouvea Atoll (Fig. 1) have been listed as UNESCO World Heritage Area, under the name of 'Lagoons of New Caledonia; reef diversity and associated ecosystems'.

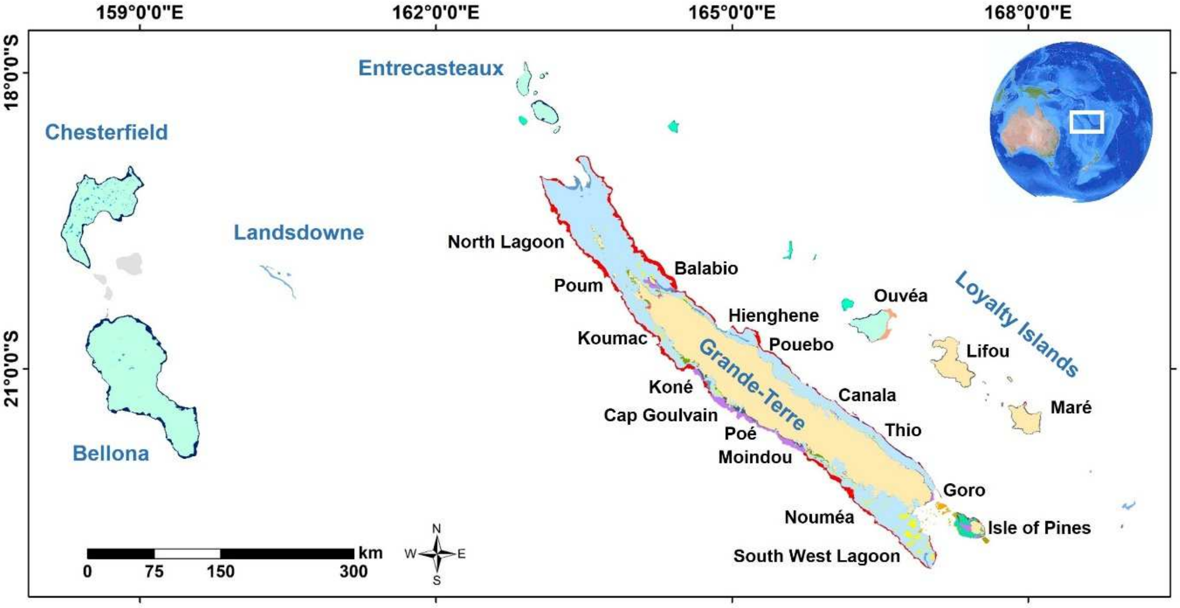

Figure 1. New Caledonia location map with its main reef and lagoon features, as well as localities cited in the study. Deep lagoons, outer barrier reefs, coastal barrier reefs, patch reefs and atoll rims are depicted in cyan, red, violet, yellow-orange and dark blue respectively. While fringing reefs (green) are difficult to distinguish at this scale especially around Grande Terre, they are important features as they harbor most of the shallow seagrass beds, especially the large meadows found around Balabio, Moindou-Cap Goulvain and north of Koné.

Twelve seagrass species have been identified in New Caledonia (Payri, 2007, McKenzie et al. 2021a), including four *Halophila* species *(H. capricorni*, *H. minor, H. decipiens,* and *H. ovalis*), *Cymodocea rotundata and C. serrulata, Halodule uninervis* and *H. pinifolia*, *Enhalus acoroides*, *Thalassia hemprechii, Syringodium isoetifolium* and *Ruppia maritima*. As *Ruppia maritima* was found to only occur in brackish marshes mainly in the North West areas of Grand Terre (Duke et al, 2010), it is not discussed further. Our focus therefore is on the 11 marine species that were described for the general public in IRD (2005). Noteworthy, is the absence of species common to the rest of west Melanesia, such as *Thalassodendron ciliatum* (McKenzie et al. 2021a). In New Caledonia, seagrass are found in a variety of estuaries, lagoons, channels, and reef (fringing, intermediate, barrier) areas. Most seagrass beds are located in shallow waters (<10 m depth), but *Halophila decipiens* and *H. capricorni* occur in the deeper lagoon areas (down to 60 m) (Garrigue 1987, IRD 2005).

The flora of the South-West Lagoon of New Caledonia was intensively sampled by discrete dredging in 1984-1986 (Garrigue 1987), as well as by SCUBA in 1989-1991 (Garrigue and Di Matteo 1991, Garrigue et al 1992). This sampling included large lagoonal areas deeper than 10 meters and down to 45 meters. Then several flora sampling campaigns undertaken around New Caledonia in 2004-2015 (CORALCAL 1-5) also provided observations for the oceanic slopes and for some lagoons.

In 2004, to fill critical gaps in basic ecosystem knowledge, the ZONECO New Caledonia program funded a remote sensing-based project on 1) coral reef habitat mapping and fisheries, and 2) seagrass inventory and mapping. The scope for habitat mapping was limited to five pilot sites in the Moindou, Koné, Thio, Balabio and Lifou Island areas, to be processed with the most recent 2.4-meter spatial resolution satellite imagery (from Quickbird or Worldview-2 satellites). Seagrass mapping at the scale of Grand-Terre was undertaken using Landsat images at 30-meter spatial resolution. Since seagrass beds were included in the areas targeted for coral reef habitat maps, high spatial resolution seagrass maps were also derived for the aforementioned five sites. Seagrass-targeted areas were limited to shallow waters, from the intertidal zones down to 10 m at most, and generally down to 5 m. In a habitat and seagrass bed mapping context, several tens of stations per site are required for ground-truthing and accuracy assessment (Andréfouët et al. 2003, Andréfouët 2008). The field protocol for ground-truthing followed a fast-protocol for the collection of visual qualitative and semi-quantitative data, and photographic records, and was similar in scope to the Medium-Scale Approach defined to visually describe benthic habitats in fish or invertebrate surveys (Clua et al. 2006). Benthic cover was measured using a semi-quantitative scale from 1 to 10 that linearly covers the 0-100% gradient (1=0-10%, to 10=90-100%). Additional occasional work included measurements of cover and biomass per species in 50 cm by 50 cm quadrats, to derive a cover-biomass relationship for different meadow types (Scamps 2005, Fontan 2009).

Additional New Caledonia shallow *in situ* inventories were conducted, without mapping, over the course of different projects. Species inventories were undertaken in shallow areas of Ile Des Pins, Goro, Cap Goulevain, Poe, and between Poum to Voh fringing sites. The 4-day cruise HERB-EST aboard RV Alis in 2012 also specifically surveyed seagrass beds between Canala and Hienghene on the East Coast. All these inventories provided discrete records only, for about 8 to 15 stations per site per day down to a maximum depth of 10 m. They were undertaken through timed searches (generally 20 minutes) by 2 snorkelers deployed at each station and during which the presence or absence of species was noted. Stations were selected by visual examination of various available satellite imagery and through Google Earth ® by one of us (SA) to identify likely areas of seagrass presence. Searched areas per station covered roughly a maximum of 1 hectare depending on the size of the seagrass bed. In addition, oblique and vertical photographs (wide and medium angle) were systematically collected *in situ* to assess density on semi-quantitative scales (1 to 10, as above) and canopy height.

All identifications reported here were performed by three of us (CP, CG, SA). Since 2004, sampled species were identified according to Kuo and Hartog, (2001) and Waycott et al. (2004) taxonomic keys, although in several instances *Halophila* specimens could be only described as *Halophila* sp. For some of the early surveys, specimens were collected and conserved in herbarium. During surveys related to habitat mapping, specimens were usually not collected, and identification was performed 'on the fly' with photographic records that were more systematic after 2008. Analog cameras typically used before that year were limited to 36 slides, and most stations only have written records on underwater paper sheets. As of ca. 2010, digital compact cameras with increased autonomy allowed for, as in 2021, the recording of hundreds to thousands of pictures in just one day of field work.

2.2. Component of the framework

The compilation across time of the New Caledonia data sets, in particular with the use of remote sensing based products starting in 2004, allowed us to streamline the process in a suite of non-spatial data (local field inventories) and spatial data (maps from remote sensing) at different scales. The levels of information are complementary and linked through a series of nested iterative actions (stratification, generalisation, thematic simplification, compilation and aggregation) that are explained hereafter. Considering that similar implementations could be planned for different Indo-Pacific areas, this section (2.2) generically describes the different individual components of the framework. The next section (2.3) focuses on the links between components and provides a complete framework flow-chart (Fig. 2).

Scales

We broadly consider three different spatial scales. The national scale (or **Level 0**) implies work covering the entire country of interest potentially up to several tens of thousands of square kilometres. Conversely, the site scale (or **Level 1**) is limited to any site defined by some geomorphological, geographical, environmental, customary or management criteria and boundaries. Typically, this scale covers a few hundred to a couple thousand square kilometres. These limits are obviously fuzzy as they depend on the sizes and the coastline lengths of the islands, the extent of their reef and lagoon systems, and their natural and administrative limits. Finally, a seagrass bed type (or seagrass community) is defined by specific benthic attributes that can be measured or assessed visually at a spatial scale of one to a few hundred square meters. This corresponds here to the field station scale, and which also corresponds here to a sampling unit (**Level 2**). Level 2 attributes can include: seagrass species composition, density and biomass; sediment and substrate characteristics; and presence of other remarkable organisms (corals, macroalgae, sponges, ascidians, seagrass epiphytes etc). Note that a field station is therefore typically a collection of notes, photographs, quadrats or transects. An individual quadrat or transect or photograph collected within a field station would be a Level 3 unit of description, which is not explicitly addressed hereafter, as all data are consolidated at Level 2, Level 1 and Level 0.

National-scale Millennium Coral Reef Mapping Project data

The Millennium Coral Reef Mapping Project (MCRMP) has mapped most Indo-Pacific countries (including all PICTs) using Landsat satellite images at 30-meter resolution. The maps describe a number of geomorphological classes that are part of a global hierarchical typology of reef geomorphological classes (Andréfouët et al.; 2006, Andréfouët and Bionaz 2021). In a recent review of the relevance of MCRMP products for research and management, Andréfouët and Bionaz (2021) pointed out their use to indirectly enhance the mapping of seagrass beds, in the Caribbean (Wabnitz et al. 2008) or in Indonesia (Torres-Pulliza et al. 2013). Indeed, among the mapped MCRMP geomorphological classes, several are characteristic of where seagrass beds usually flourish, such as the sedimentary terraces (in a fringing, patch or barrier reef environment), inner slopes, shallow lagoons and basins, deep lagoons, and some wide reef flats.

MCRMP products can be used during two very different phases of a national-scale assessment: 1) to infer through general contextual knowledge where seagrass beds could occur and guide the selection of field sampling sites, 2) to generalize, with a very simple type of niche model, the distribution of seagrass beds from their documented occurrences within certain geomorphological classes.

Hereafter, we will refer to a MCRMP product (or any other similar product that might be used) as a **L0R** product, for National (Level 0) Reef map product.

Field Station-scale taxonomic identification of seagrass species

Field work included, for all field sampling units, *a minima* the identification of seagrass species that are present. Hereafter, we will refer to a series of stations with taxonomic records as a **L2SP** product, for a Local level 2 species (SP) product. The sampling protocol performed specifically for New Caledonia is described above in section 2.1.

Field station-scale characterization of seagrass bed communities

Besides species taxonomic identification (above), Level 2 field stations can be investigated to describe the seagrass community covering a surface anywhere between a few square meters up to several hectares. A variety of protocols exist that use a set number of transects, quadrats or photographic records replicated across a number of predefined strata. Qualitative, semi-quantitative, or quantitative data can provide details on seagrass canopy height, density, and biomass, as well as types of sediment, and associated organisms (Short and Coles 2001). Species composition comes directly from the compilation and aggregation of all recorded species, without any order of priority across species. A statistical analysis (e.g., hierarchical clustering) on these data can help identify representative seagrass communities and assess their similarities, but it is also possible to derive seagrass communities based on each individual variable, or combination of variables, even if some communities show little difference across these criteria.

Hereafter, we will refer to a series of stations describing seagrass communities as a **L2SCom** product, standing for Local level 2 Seagrass community-Type product. This L2SCom product is necessarily linked to a L2SP product as well since species identification data are also collected.

Site-scale detailed benthic mapping of seagrass communities

Nowadays, habitat maps derived from remote sensing images, in New Caledonia and elsewhere, are often developed to inform systematic conservation plans (Deas et al. 2014), identify conservation areas and assess sampling schemes (Van Wynsberge et al. 2012), as well as develop fishery management measures (Léopold et al. 2013). Habitat maps are derived from remote sensing images using different methods. We here choose to apply the user-oriented approach described by Andréfouët (2008). At level 1, habitat maps are typically created using multispectral satellite images at 1 to 4 meter spatial resolution. These maps do not provide discrete information, like the L2SP or L2SCom products above, but information that is spatially continuous.

For the same local site, different habitat maps can also be produced (Dalleau et al. 2010, Van Wynsberge et al. 2012, Gairin and Andréfouët 2020). They can primarily vary according to their thematic resolution, which is the number and the type of classes mapped. For instance, one map can include only a generic ‘seagrass’ presence map, while another can map different seagrass communities. The differences are inherently driven by the specific application for which the map was produced, but also by the spatial resolution of the initial remote sensing image, and by the type of field data collected (Andréfouët 2008).

If a local site is targeted for detailed habitat mapping (*i.e.*, with high thematic resolution), it is common to have an adequate number of L2SCom stations to describe the seagrass communities that are present. 'Adequate' means that the number of stations is optimized, often as a compromise across attributes such as site extent, time limitations, and budget. For instance, all the New Caledonia sites sampled for detailed habitat and seagrass mapping (L1SCom, see example below) were each ground-truthed over a maximum of 5-day by a team of 2 to 3 surveyors (plus a boat pilot).

However, even given the optimal combination of size/time/budget, all L2SCom seagrass communities identified in the field cannot necessarily be mapped using remote sensing, because in most cases, many communities will not be discriminated optically on remote sensing images (Andréfouët et al. 2003). Therefore, the habitat map realistically can only represent a subset of seagrass communities and may only provide a thematic simplification of the actual richness on site.

Hereafter, we will qualify a Level 1 map of seagrass communities as a **L1SCom** product, for Local level 1 Seagrass community Type map product.

Site and national-scale map of species distribution

If species identification L2SP data have been collected across space and time at different sites, it is possible to compile the information and show the location of each species record. This compilation can be performed at Level 1 (site scale) or Level 0 (national scale), yielding a **L1SP** or a **L0SP** product respectively. In this case, the information is not a continuous map, but a suite of discrete points with known occurrences of seagrass species. Records of species absence at a given station may also be compiled.

National-scale map of seagrass communities

If several L1SCom maps of seagrass communities have been created, it is possible to assemble this information and show the locations of each type of seagrass community. Such a compilation would yield a **L0SCom** map product. Ideally, the whole country could be reconstructed with a mosaic of individually mapped sites, but this is unlikely for most countries.

When the set of L1SCom maps is not exhaustive enough to cover the entire national or archipelagic area, a map of seagrass communities can be derived from coarser resolution satellite images covering the whole country (such as a set of 30 meter spatial resolution Landsat images, or 10 meter Sentinel-2 images). However, compared to collating a suite of L1SCom maps, each of them with their own mapped seagrass types, the production of a national-level map of seagrass types from 10-30 meter resolution satellite imagery generally implies an additional simplification of the typologies defined for each individual local L1SCom sites mapped at a resolution of 1 to 4 meters. Such simplification was necessary for instance for Caribbean-Atlantic countries with only 3 classes of seagrass beds categorised according to density (Wabnitz et al. 2008).

Another option to derive a national-scale map of seagrass communities is to use the L0R MCRMP national map to infer, through a generalization across the relevant geomorphological units, the distribution of local seagrass communities. However, this approach also implies a substantial simplification of typologies.

2.3. Framework's flow chart

A summary of the components and products that can be created hierarchically to improve spatial knowledge of seagrass species and communities at different scales is provided in Figure 2 through a flow chart connecting data sets, scales and actions (stratification, generalisation, thematic simplification, compilation and aggregation).

If we consider that, hierarchically, L0 is at a lower level than L1, and L1 itself at a lower level than L2 (L0<L1<L2), stratification consists in defining a stratum from a lower level to sample at a higher level. For instance, sampling sites for L2SP inventories may be chosen by stratifying L1SCom or L0R existing maps into a set of distinct seabed types or reefs habitats.

Conversely, generalisation consists in systematically applying a higher level of knowledge to a lower level – though this should be done with care and assumptions clearly outlined. For instance, if a L1SCom seagrass community is found in an area characterised by a particular L0R habitat class, then that community's presence may be generalized to all areas displaying the same L0R habitat. In essence, this approach is equivalent to a very crude one-variable only niche model.

Thematic simplification occurs when several L2SCom communities are merged into one L1SCom or L0SCom community because all the individual communities cannot be accurately mapped with remote sensing images (Andréfouët 2008). This approach was used, for instance, when a 'shallow low density *Halophila* sp' L2SCom community and a 'shallow low density *Halodule pinifolia'* L2SCom community had to be merged as a less precise multispecies L1SCom 'shallow low density *Halophila* sp. or *H. pinifolia* community' because they cannot be distinguished on remote sensing images.

A compilation consists in consolidating multiple data sets at one level into a single lower level data set, without generalization or thematic simplification. For instance, multiple L2SP data sets are compiled in the L1SP map.

Finally, aggregation is defined here when combining multiple individual species lists to produce a community description.

A number of additional actions and loops are possible (red arrows in Fig. 2). Specifically, once a map is available (L0R or L1SCom), it can be used to stratify additional sampling, to collect new gap-filling L2SP and L2SCom data. Additionally, once new species or community sampling is available at local levels, new updated generalisation can be performed to refine knowledge. Therefore, the framework can be seen as being developed and refined iteratively.

Should the framework be applied elsewhere than New Caledonia, a number of steps are optional if the skills or funding are not available. Typically, all map products (L0SCom, L1SCom), with the exception of L0R which are already available for most Indo-Pacific countries, are optional. Thus, seagrass knowledge can be developed based on discrete L2SP, L1SP and L0SP products.

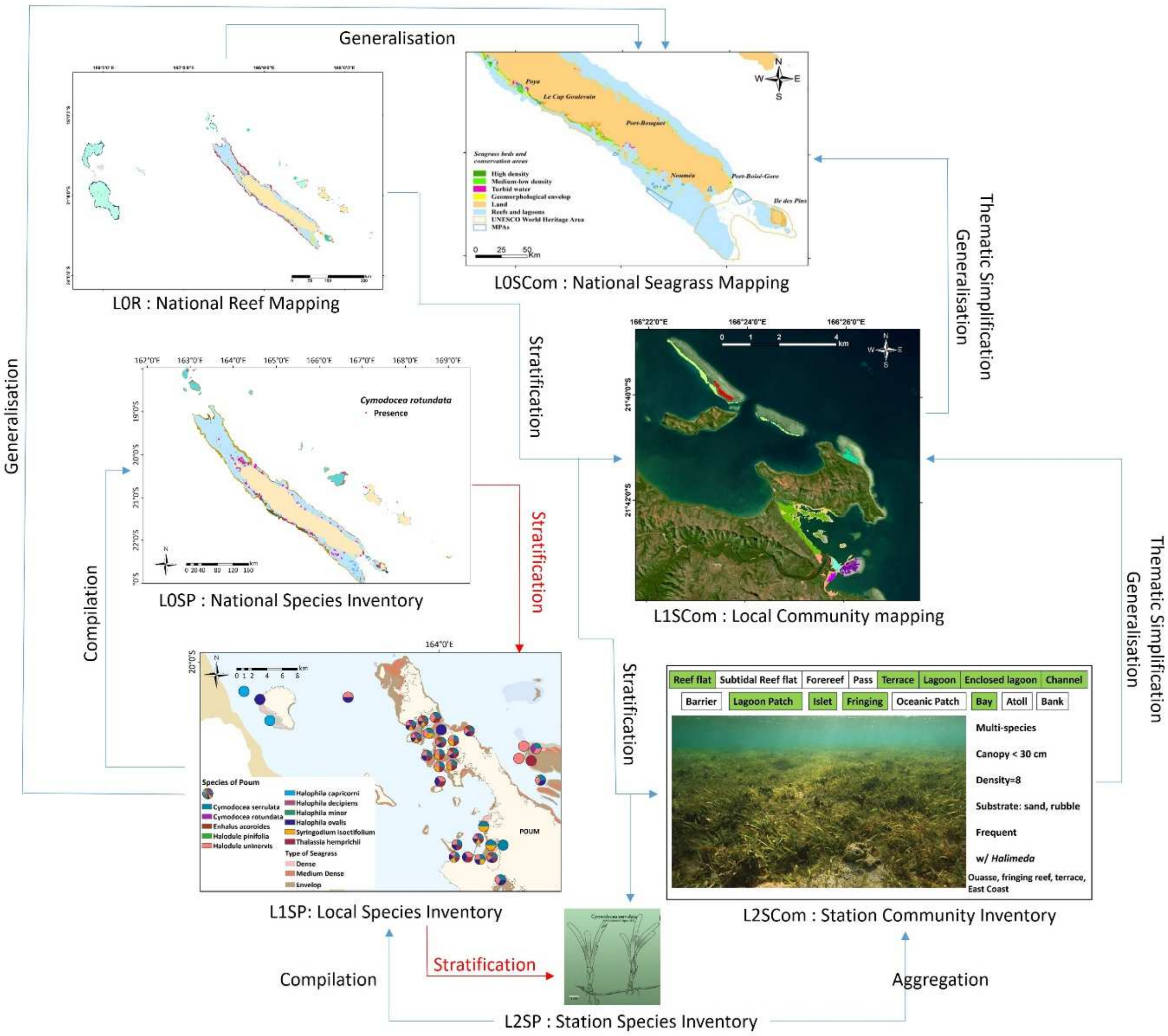

Figure. 2: Flow chart summarizing the hierarchical framework to enhance spatial knowledge on seagrass species and communities at different scales, from field sampling station level, to local sites and the national scale. Individual products in the flow chart are shown at full resolution in Figures 3 to 9. Phases of stratification, spatial generalisation, compilation, aggregation and thematic simplification link different products and scales. The stratification arrows in red highlight a possible iterative, looping, process.

4. Results and Discussion

4.1. Implementation of the framework for New Caledonia

Over the course of several field surveys and projects undertaken from 1984 to 2017, we have been able to develop a substantial database around New Caledonia seagrass and products derived therefrom, with examples presented in Figures 3-9. Concise comments are provided for the L0R, L0SCom, L0SP, L1SCom, L1SP, L2SCom and L2SP products, which are sometimes presented together to highlight the complementarity of products within the hierarchical framework.

L0R: The MCRMP product has been available since 2004 and is presented in detail in Andréfouët et al. (2009) as well as in the French coral reefs atlas (Andréfouët et al. 2008). In short, the latest version of the MCRMP product describes ~36,200 km^2 of reefs and lagoons across 174 geomorphological classes (Gairin and Andréfouët, 2020), several of which include a high frequency of seagrass species occurrences (based on subsequent L2SP surveys, see below).

L2SP/L1SP: Field identification of seagrass species took place across a total of 805 L2SP sampling stations. Figure 3 is an example of a L1SP species inventory for the Poum site. Figure 3 illustrates the compilation of L2SP level products over 34 stations to produce a L1SP species inventory product covering the entire Poum site.

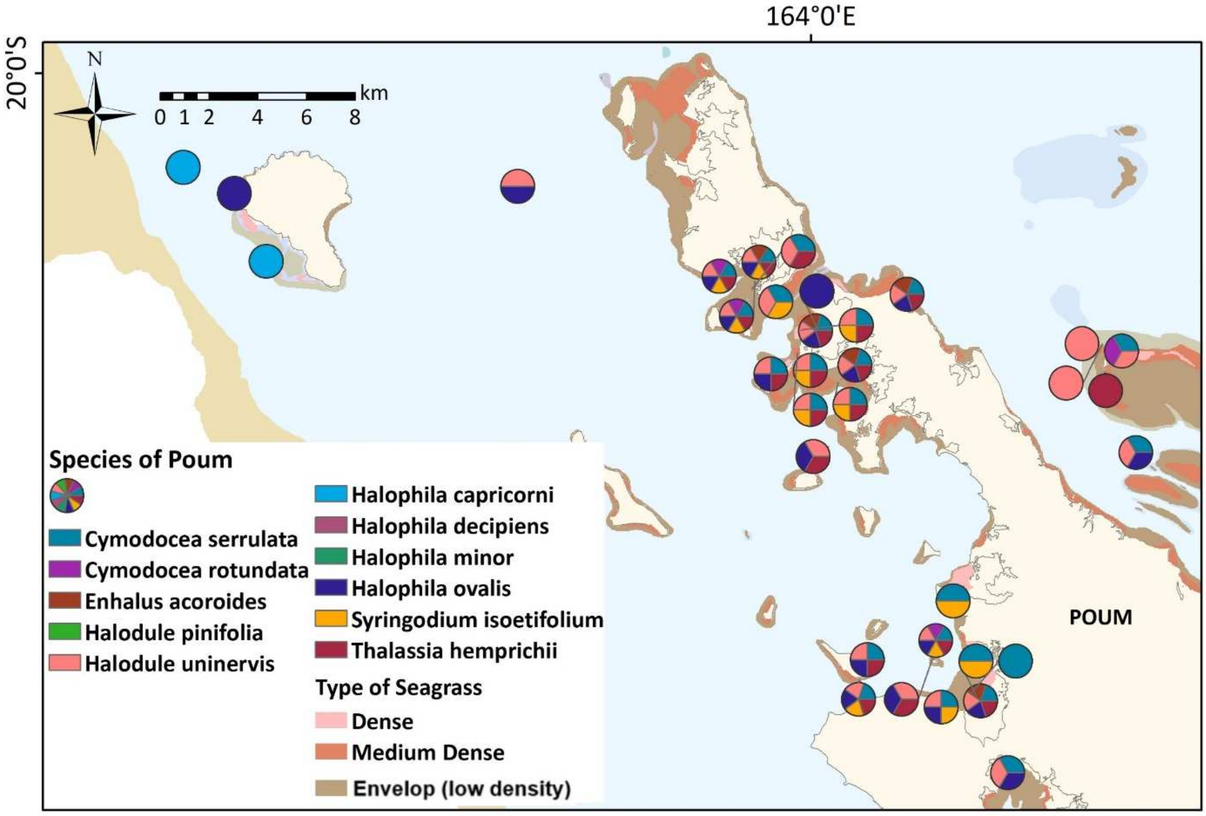

Figure. 3: Example of field identification of 11 seagrass species (L2SP product) for the Poum area, here overlaid on top of the L0SCOM map product (with 'dense', 'medium dense' and 'envelop' (shallow and low density, see text explaining the L0SCom product), see Figure 9). Light blue shades are deep (>10m) lagoon areas.

L2SCom: Based on *in situ* surveys – with the last one performed in 2017 - recording species composition, density, canopy height, sediment, and abundance of other organisms (coral and sponges), we described a total of 80 different seagrass communities, all characterized by a unique combination of these variables. These communities have been included in the habitat ID card catalogue developed for all reef and lagoon habitats in New Caledonia (Andréfouët 2014), and were also created for Indonesia (Ampou et al. 2018) and other Indian Ocean sites (Juan de Nova, Mayotte, Baa atoll in Maldives SA unpublished data). Several of these ID cards are presented in Figures 4 and 5. They show the presence or absence of seagrass communities within each geomorphological L0R strata, as well as their main characteristics. The ensemble emphasizes the hierarchical structure of the information.

The structural and taxonomic differences that define these 80 seagrass communities do not necessarily imply that the functioning and ecological roles of, threats to, and the services provided by seagrass are different across individual communities, since many may differ by only one single variable (e.g., sediment). However, given currently very limited knowledge that could help categorize the different functional groups of seagrass beds in New Caledonia, this aspect warrants further investigation. This work could *in fine* provide a typology of New Caledonia seagrass beds and their functions as Carruthers et al. (2007) presented for West Australia's seagrass beds.

L1SCom: Transitioning through thematic simplification from station-level community characterisation (L2SCOM) to their mapping using remote sensing data (L1SCom), yielded between 1 (*e.g*., Lifou) and 14 mapped communities per site (*e.g.,* Thio). Figure 6 shows a seagrass map product for the Thio site with the seagrass L1SCom typology from which it was derived.

L0SP: The national-scale map of species distribution achieved through the compilation of all L2SP stations is presented in Figures 7 and 8. We choose to display presence and absence data, although absence data should be interpreted with caution as it can never be ascertained that a given species is truly absent from a site after a 20' search time, except generally for the taller, easy-to-spot, *Enhalus acoroides*. Presence/absence records are biased by canopy height, which is also known to be season dependent. With this warning in mind, several patterns are compelling. The 11 species map-ensemble highlights the general lack of seagrass on the barrier reef system, except for some *Halophila* spp and some *Halodule uninervis* beds found on the inner sedimentary terrace. The lack of seagrass in higher energy environments (reef flat of barrier reef or oceanic-exposed fringing reef) is congruent with the absence of *Thalassodendron ciliatum* species in New Caledonia, but which has been recorded on barrier reefs in Solomon Islands (CP, pers. observations), and in Anatom island in South Vanuatu just north of New Caledonia by Green and Raynal with collected specimen in Port-Vila, Vanuatu (http://publish.plantnet-project.org/project/vanuaflora_en/collection/pvnh/specimens/details/8259). *Halophila capricorni* has a split distribution in New Caledonia's north, south and east deep lagoons. *Enhalus acoroides* follows a patchy pattern, depending on the location of estuaries and turbid areas. This species was never found in medium energy environment in New Caledonia, such as lagoon-exposed reef flats for instance, while this is common elsewhere in Melanesia or Asia (CP, SA, pers. observations). In contrast, *Cymodocea* spp, *Halodule* spp and *Thalassia hemprechii* are fairly common all-around Grande Terre, although *C. serrulata* is rarer on the east coast. The outer islands are less diverse: with six species in the waters of the Isle of Pines in the south, five in the Loyalty Islands, three on Entrecasteaux reefs and four species in the Chesterfield-Bellona lagoon and on its reefs (the latter not shown in Figs. 7-8, but see caption). These patterns suggest that both the distance to Grande Terre (considered as the closest possible origin), currents and availability of habitats are important drivers of seagrass distribution in remote sites of the Coral Sea, as observed for other taxa such as giant clams (Van Wynsberge et al. 2017).

[✓ Reef flat] [✓ Subtidal Reef flat] Forereef Pass [✓ Terrace] [✓ Lagoon] [✓ Enclosed lagoon] [✓ Channel]

[✓ Barrier] [✓ Lagoon Patch] [✓ Islet] [✓ Fringing] [✓ Oceanic Patch] [✓ Bay] [✓ Atoll] [✓ Bank]

Halophila ovalis

Canopy < 5 cm

Density=1

Substrate: sand

Frequent

Koné lagoon, West Coast

[✓ Reef flat] Subtidal Reef flat Forereef Pass [✓ Terrace] Lagoon Enclosed lagoon [✓ Channel]

[✓ Barrier] [✓ Lagoon Patch] [✓ Islet] [✓ Fringing] Oceanic Patch Bay Atoll Bank

Cymodocea rotundata

Canopy < 30 cm

Density=9

Substrate: sand

Frequent

Koné, barrier reef, terrace, West Coast

[✓ Reef flat] Subtidal Reef flat Forereef Pass [✓ Terrace] Lagoon Enclosed lagoon [✓ Channel]

Barrier [✓ Lagoon Patch] Islet [✓ Fringing] Oceanic Patch [✓ Bay] Atoll Bank

Syringodium isoetifolium

Canopy < 30 cm

Density=8

Substrate: sand, rubble

Not frequent

w/ *Halimeda*, coral

Koumac, lagoon patch reef, terrace, West Coast

Reef flat Subtidal Reef flat Forereef Pass [✓ Terrace] Lagoon Enclosed lagoon Channel

Barrier [✓ Lagoon Patch] Islet Fringing Oceanic Patch Bay Atoll Bank

Multi-species

Canopy < 30 cm

Density=7

Substrate: sand, rubble

Rare

w/ coral (*Cyphastrea* sp.)

Islet Amédée, lagoonal patch reef, terrace, West Coast

Figure. 4: Examples of L2SCom products, or seagrass communities. Communities are mono-or multi specific, Communities are characterized by their species composition, density (or benthic cover, on a scale 1 to 10), canopy height (maximum or minimum), sediment type, and presence of other organisms. An indication of rarity is mentioned, although this can be biased by sampling. The upper tags indicate for each two-level geomorphological strata (from L0R product) if the communities were present based on current records. For instance, the last community was found only on the sedimentary terrace of a lagoon patch reefs while more combinations were found for the other types. All combinations of tags highlighted in green are possible.

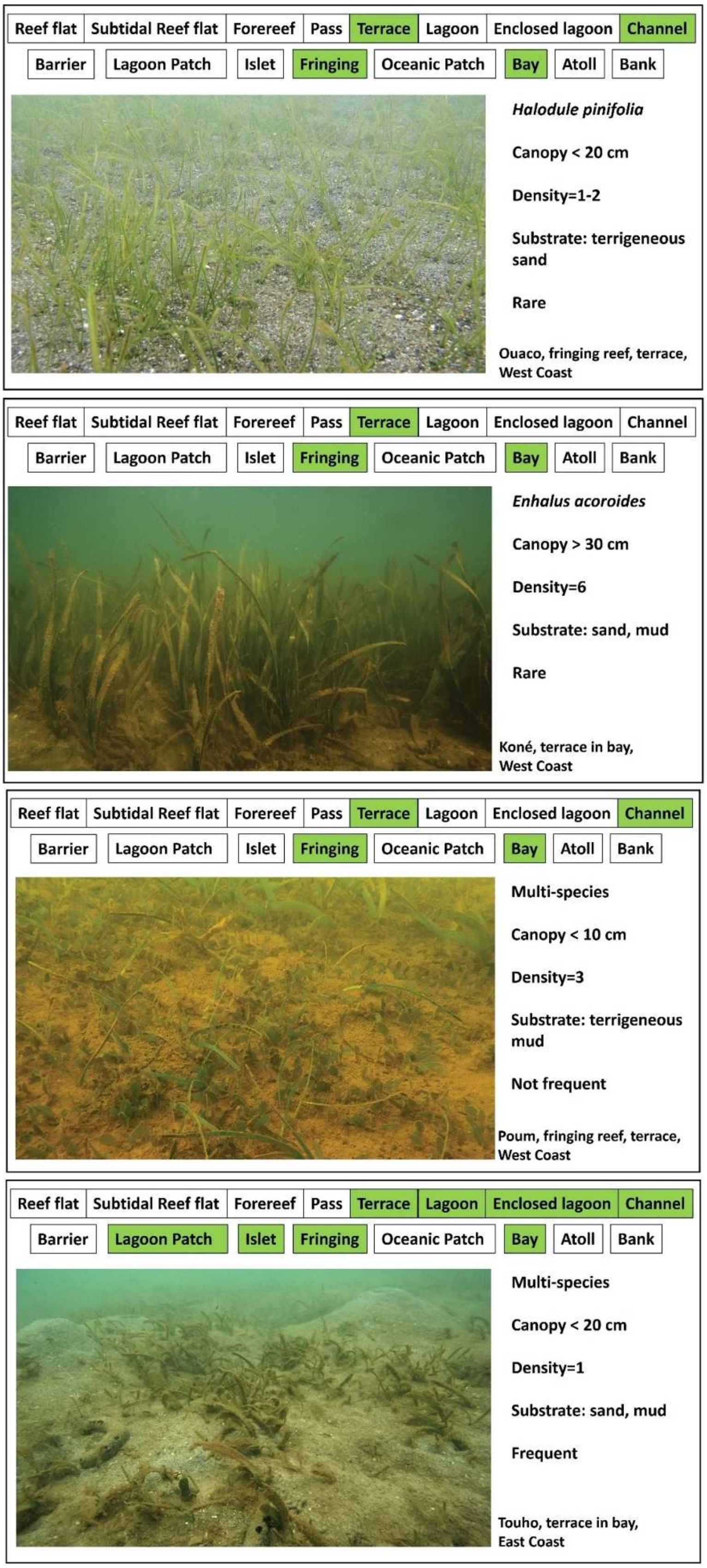

Figure. 5: Additional examples of L2SCom products, or seagrass communities, with terrestrial (fringing) influence. See Figure 4 caption for additional information.

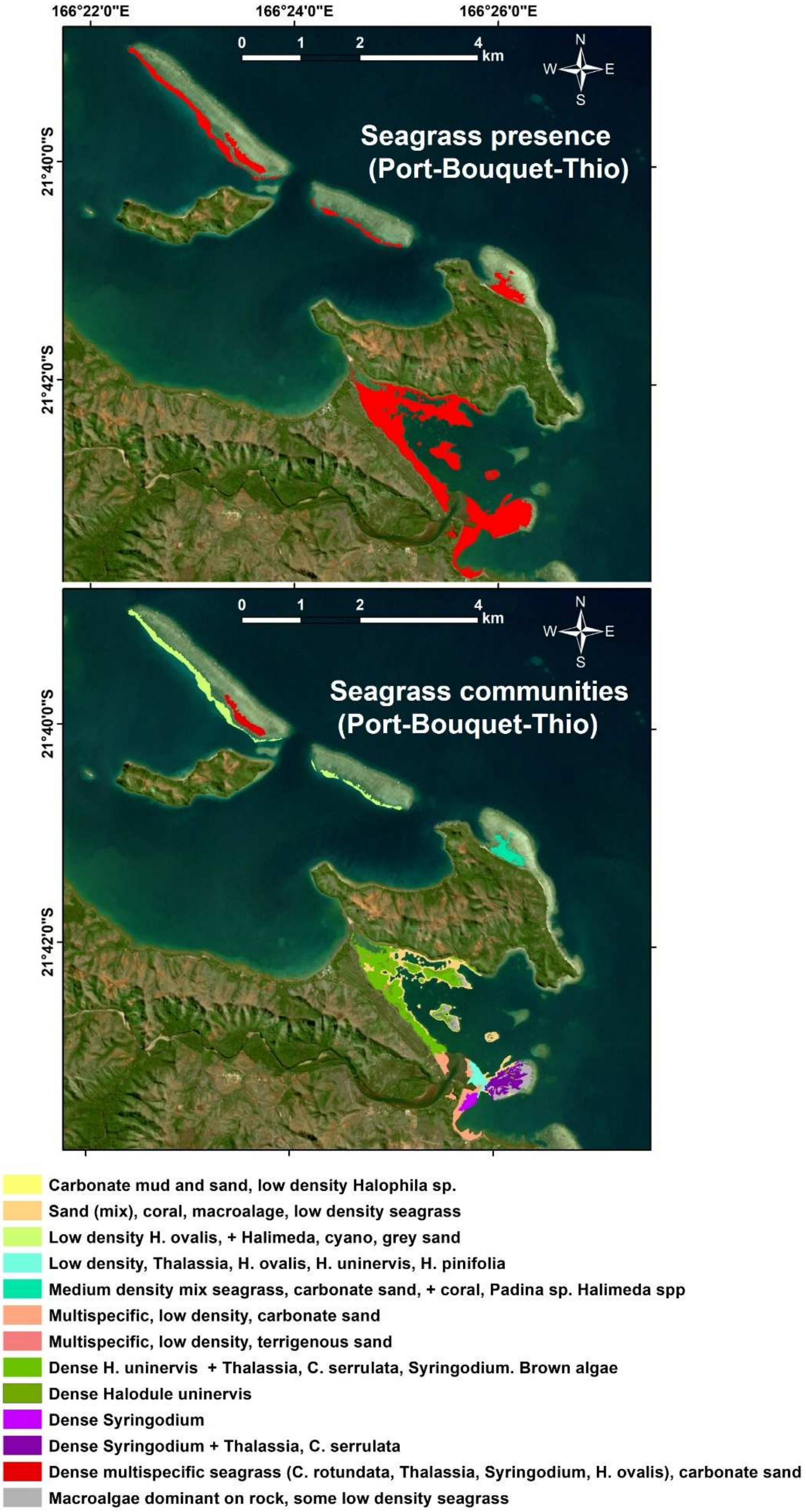
166°22'0"E
166°24'0"E
166°26'0"E
21°40'0"S
21°42'0"S
0
1
2
4
km
N
W
E
S
Seagrass presence
(Port-Bouquet-Thio)
Seagrass communities
(Port-Bouquet-Thio)
Carbonate mud and sand, low density Halophila sp.
Sand (mix), coral, macroalage, low density seagrass
Low density H. ovalis, + Halimeda, cyano, grey sand
Low density, Thalassia, H. ovalis, H. uninervis, H. pinifolia
Medium density mix seagrass, carbonate sand, + coral, Padina sp. Halimeda spp
Multispecific, low density, carbonate sand
Multispecific, low density, terrigenous sand
Dense H. uninervis + Thalassia, C. serrulata, Syringodium. Brown algae
Dense Halodule uninervis
Dense Syringodium
Dense Syringodium + Thalassia, C. serrulata
Dense multispecific seagrass (C. rotundata, Thalassia, Syringodium, H. ovalis), carbonate sand
Macroalgae dominant on rock, some low density seagrass

Figure 6: Example of L1SCom detailed shallow (0-5m) seagrass community maps for the Thio site (for site location, see Fig. 1). Top: presence of seagrass (red mask area). Bottom: seagrass community map, verified by ground-truthing for habitat mapping. Background satellite image: DigitalGlobe (now Maxtar ®) Quickbird-2 image.

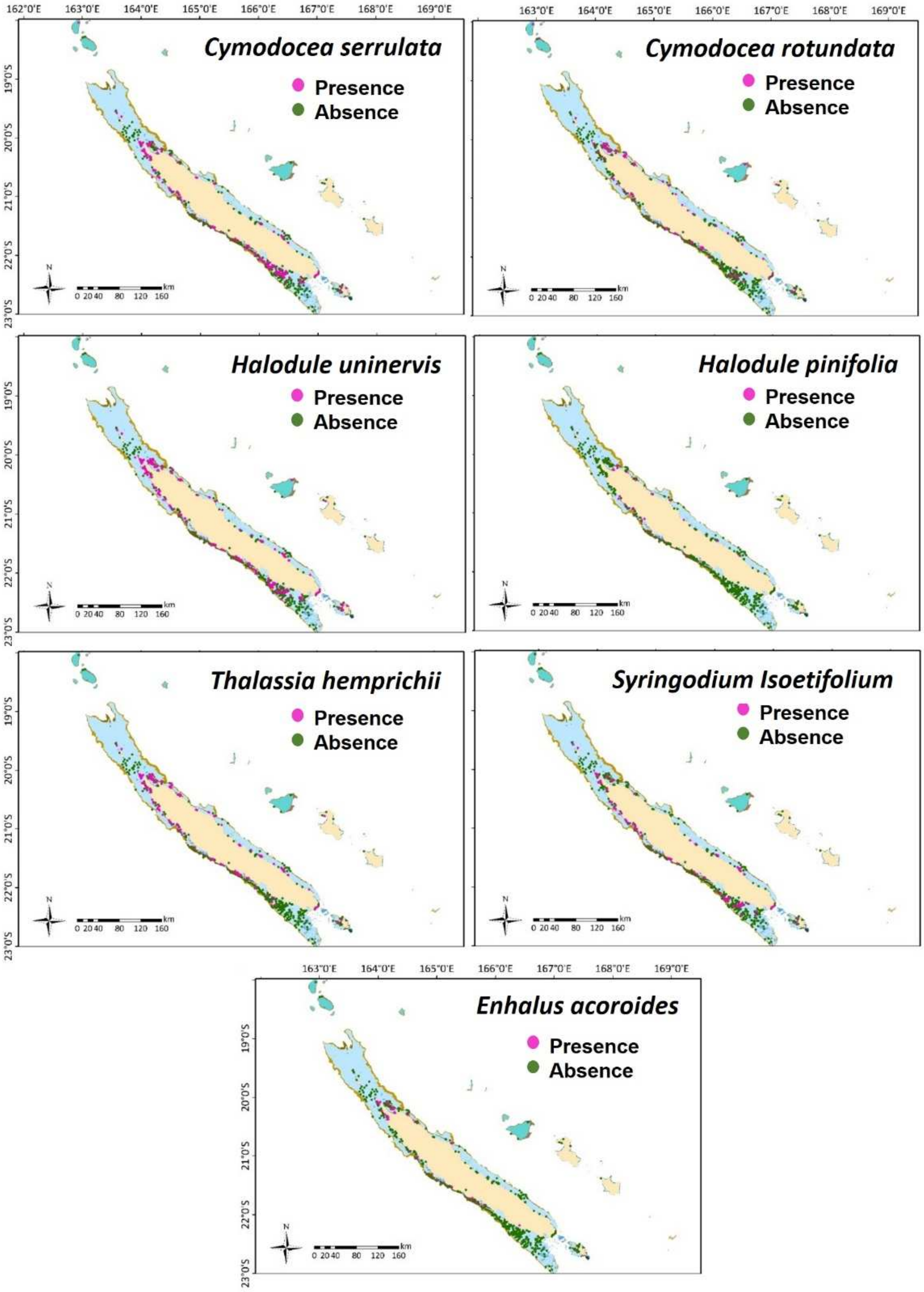

Figure 7: L0SP maps showing locations of reported presence and absence for 7 of the 11 New Caledonia species around Grande Terre, Entrecasteaux and Loyalty Islands. Not shown here, the Chesterfield-Bellona area, which also harbors *H. uninervis*.

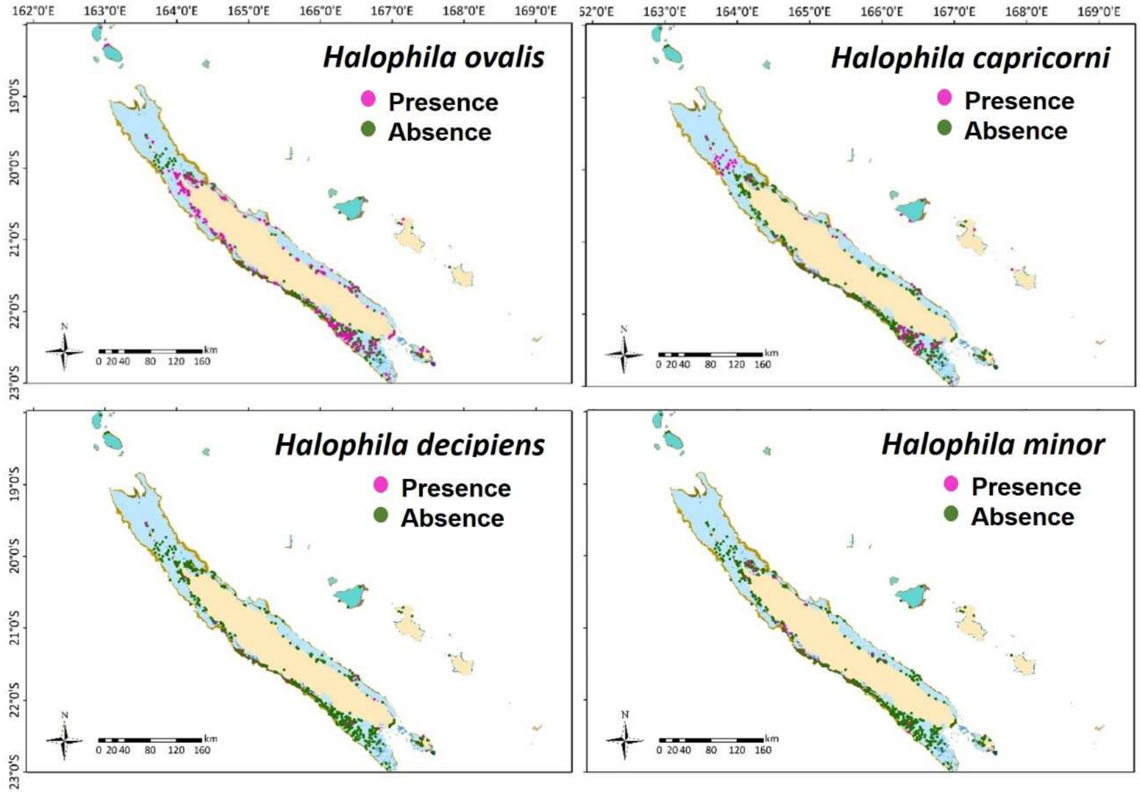

Figure 8: L0SP maps showing locations of reported presence and absence for the *Halophila* species around Grande Terre, Entrecasteaux and Loyalty Islands. Not shown here, the Chesterfield-Bellona area, which harbors *H. ovalis, H. decipiens and H. capricorni*.

L0SCom: to achieve a national-scale map of seagrass distribution using Landsat images, another thematic simplification was required. The only communities that could be mapped at this scale were the dense seagrass beds (all species included), medium density seagrass beds (all species included), and a geomorphological-based envelop that can include shallow low density seagrass beds that are not directly detectable using remote sensing images (Fig. 9). It must be kept in mind that with Landsat images (30-meter resolution), the minimum discernible unit is an object of about 1 hectare, hence the definition of 'high', 'medium' and 'low' densities also needs to be applicable at that scale. It is thus normal that 'dense' seagrass beds are much less common than medium-density beds in L0SCom products and where they do occur, they are limited to rare very dense and wide areas (Fig. 9). The L0SCom low, medium and high densities correspond to the semi-quantitative benthic cover index used for L2SCom communities (Figs. 4-5), with densities ranging from 1 to 4, 5 to 7, and 8 to10 respectively. The drastic thematic simplification needed for national scale L0SCom is consistent with the simplification that was required for other regions, such as the mapping of Caribbean seagrass beds with Landsat images (Wabnitz et al. 2008). Results suggest that up to 942 km^2 of shallow seagrass are present in New Caledonia, although only 356 km^2 are medium – to dense meadows (Andréfouët et al., 2010). Seagrass also likely occur on 41

km^2 of turbid areas in estuaries but this cannot be ascertained with remote sensing only. In addition, the occurrences of deep *Halophila* spp in the north, east, and south lagoons (Fig. 8) suggest that deep lagoons defined in the L0R product could also be added as a second envelop for deep species, although most characteristics remain unknown in terms of meadows structure, including density. Hence, more field sampling effort, and research to assess how to use and combine existing multi-beam bathymetry, acoustic imagery, rugosity and sediment data to infer seagrass distribution would be a priority to exhaustively assess seagrass occurrence in deep lagoons.

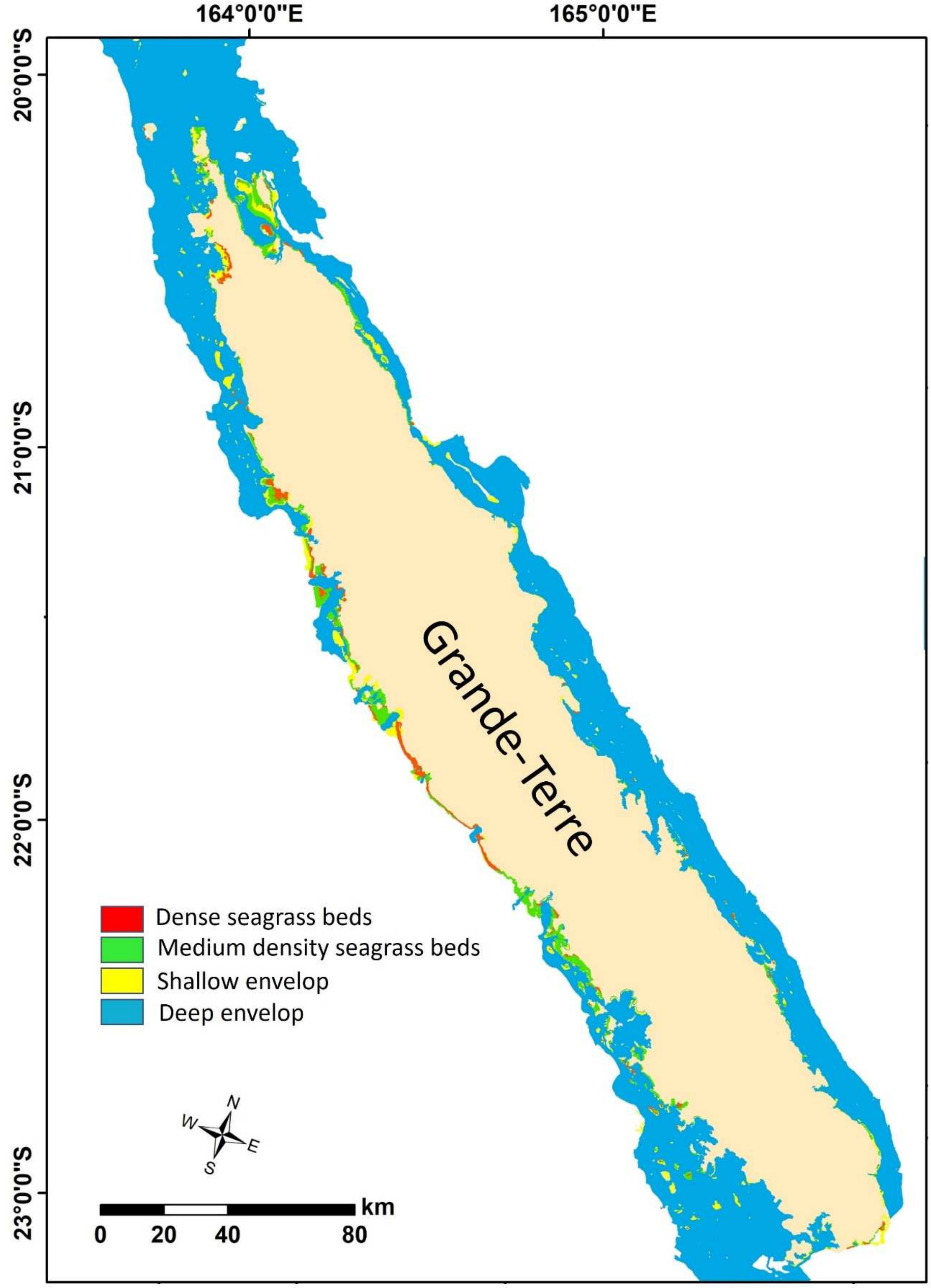

Figure 9: L0SCom map around Grande-Terre. Three classes of shallow seagrass beds can be mapped at this scale (high density, medium low density, and a very low density in the form of a geomorphological envelop that comes from the L0R map product). The deep envelop corresponds to the maximum possible distribution of deep *Halophila* species in the lagoon.

The suite of products presented for New Caledonia (Figs 3-9) illustrates what could be achieved for other areas when applying the spatially explicit hierarchical framework presented in Figure 2. The framework relies on representativity and exhaustivity as the main criteria to reference products between each hierarchical level, assess the level of knowledge, and identify gaps (Andréfouët 2008). Here, only the L0SCom (and the L0R) product is spatially exhaustive and covers all of New Caledonia. While spatially exhaustive (Fig. 9), the L0SCom product is thematically oversimplified, as the number of classes of seagrass beds (three shallow classes, plus a deep envelop) is a drastic simplification of the L2SCom typology of communities that can be described after fieldwork (Figs 3-6). Given current advances in technology, it will never be possible to map the distribution of the 80 L2SCom seagrass communities identified for the whole of New Caledonia. It is however possible to map a number of L1SCom seagrass communities (Fig. 3), based on ground-truthing and very high-resolution images. Actually, L1SCom maps could be created and compiled at the scale of New Caledonia without many technical or conceptual issues, but their production would require an expansive and costly field survey as well as high resolution mapping program - estimated in 2021 at around half a million US dollar or 400,000€ (excluding salaries).

In addition to evident gaps in L2SP, many shallow sites have yet to be mapped at the L1SCom level. We suggest that priority areas for L1SCom include UNESCO World Heritage Areas such as the large shallow Ouvea atoll and the Poe lagoon, which is widely used for recreational activities and has recently been subject to green tides (Brisset et al. 2020). In general, all the wide fringing reef flats around Grande Terre are of interest, such as those visible in Figure 3, for which no L2SCom or L2SP observations were recorded. Deep communities are also of interest, but no spaceborne or airborne optical remote sensing images can provide such information directly, and acoustic imaging and mapping would need further trials (Chevillon 2000, Lee and Lin 2018). In-water optical sensors (cameras, drones, etc) have better capacities in that regard, but require adequate logistics to be deployed, and significant post-processing as well. Finally, several on-going ecology and conservation programs are in need of better seagrass products, especially at L1SCom and possibly L0SCom levels. These applications are discussed in the next section, in the context of the framework presented here.

4.2 Framework's relevance to research, monitoring, conservation and resource management in New Caledonia

Information on seagrass species' presence/absence, types of communities, and related maps at different scale, are fundamental for research, conservation and management decision making. The implementation of the framework described above and the identification of priority gaps to be filled must be driven by its application to research and management cases. Among them, recurrent topics in New Caledonia include: 1) better assessment, monitoring and conservation of seagrass-specialist mega-fauna, such as the dugong; 2) the management of sea cucumber fisheries, including for the high commercial value species *Holothuria scabra*; 3) estimation of the proportion of habitats already included in conservation zones, for instance, the UNESCO World Heritage Areas encompassing a great part of the vast lagoon and reef areas of New Caledonia since 2008. Other applications exist, but we limit our demonstration and scope to these three topics.

Dugongs are herbivorous marine mammals broadly distributed in Indo-Pacific coastal waters, where they tightly associate with seagrass meadows. They play a unique ecosystem role (Pimiento et al. 2020), while also bearing a strong cultural and spiritual value for local communities (Marsh 2011). The species is currently listed as vulnerable under the Red List of the International Union for Conservation of Nature (IUCN), but small and isolated populations are at high risk of extirpation (Marsh and Sobtzick 2019). New Caledonia is hosting a fragile (426 ± 134 to 717 ± 171 individuals estimated in 2008-2012; Hagihara et al. 2008), yet globally important population (Garrigue et al. 2008). Aerial surveys have shown the highest densities on the west coast of Grande Terre, in habitats characterised by shallow seagrass according to L0SCom (Cleguer 2015; Cleguer et al. 2020). Satellite tracking of several individuals has revealed intense use, interpreted as feeding, in relatively deep, unmapped, waters (> 10 m), specifically in the lagoons surrounding Nouméa and Koné (Derville et al. in press). Since dugongs may indicate seagrass presence (Hays et al. 2018), their movement patterns can be used to inform future sampling meant to improve L1SCom coverage in deep lagoons (Fig. 10). Such megafauna-informed seagrass investigation has been successfully applied with green turtles tracked in the Chagos Archipelago (Esteban et al. 2018). Conversely, improved L2SP and L2SCom sampling within core areas of dugong use would provide new information about the diet of dugongs in New Caledonia. Over their global range, dugongs consume a wide variety of seagrass species (covering all genera occurring in New Caledonia), including low biomass genera *Halodule* and *Halophila* (Marsh et al. 2011). However, diet selectivity appears to be highly variable both spatially and seasonally. Hence, further investigation of dugong-seagrass associations within the L2SCom seagrass communities identified over New Caledonian lagoon and reef habitats is warranted.

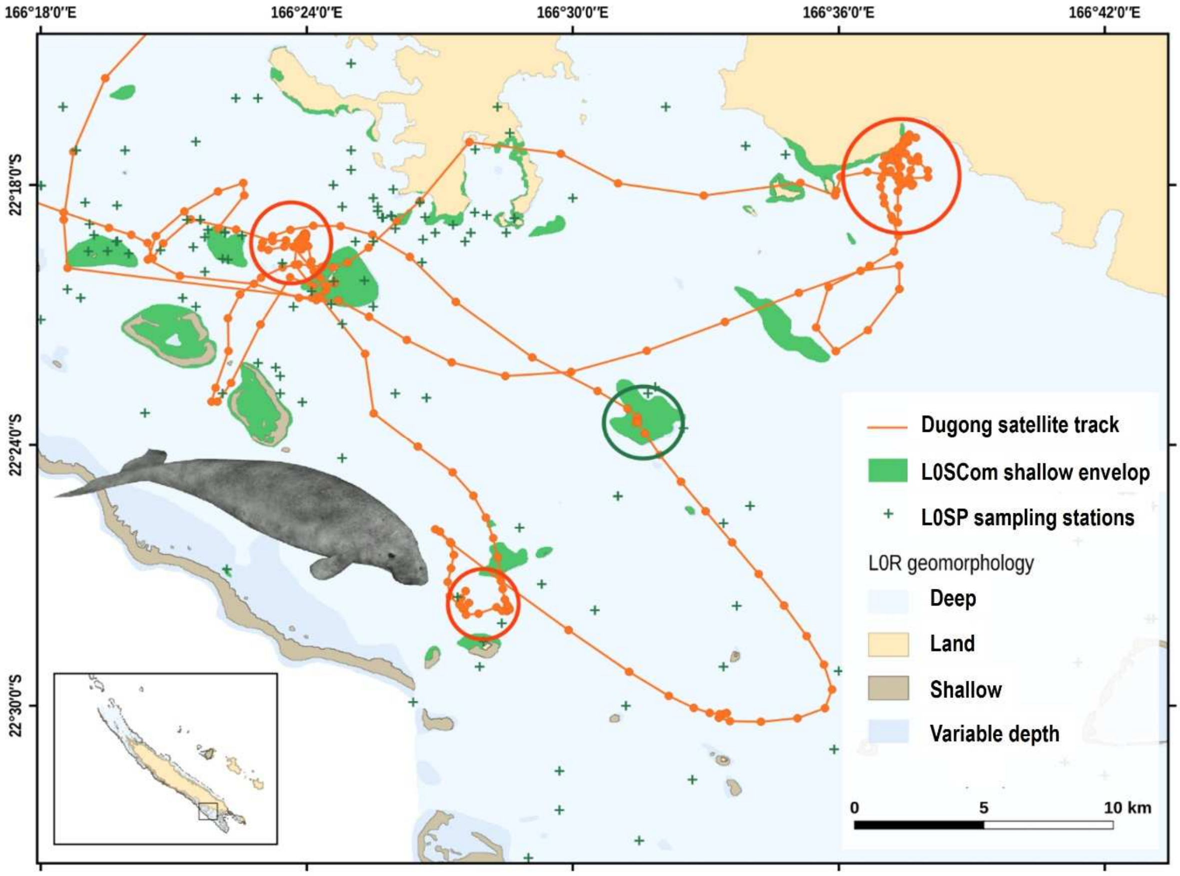

Figure. 10: Dugong satellite track can be used to identify potential deep seagrass beds locations not identified on shallow seagrass bed maps. Here, tracks overlayed with L0R, L0SP and L0SCom products in the lagoon surrounding Nouméa. Red circles delineate sinuous and slow movements interpreted as feeding behaviour occurring in deep areas where the current L0SCom shows no seagrass and that warrant further investigation. The green circle delineates an area of potential feeding within a known seagrass bed where further sampling would provide useful insights into the dugong's diet. The satellite track was recorded with an animal tagged in 2013 (see Cleguer 2015 and Cleguer et al. 2020) and was interpolated at 1 position per hour (Derville et al. in press).

Holothuria scabra and its close relative *H. lessoni* are two of the most prized commercial sea cucumber species currently exploited in New Caledonia from seagrass beds. Other commercial species of lesser value commonly found in seagrass beds include *Actinopyga echinites, A. miliaris, A. spinea* and less commonly several species of the *Stichopus* and *Bohadschia* genera (Purcell et al. 2009). Management of sea cucumber fisheries at national and site scales benefit from detailed L1SCom community maps that allow areal extrapolations of stock estimates based on species densities measured from *in situ* transects (Leopold et al. 2013). Typically, different exploited species densities emerge from different seagrass communities, assuming no other anthropogenic effects have interfered (such as fishing itself) (Purcell et al; 2009, Jimenez et al. 2016; Tagliaferro 2018). Conversely, sea cucumber stock assessment sites can contribute to enhance knowledge of seagrass community distributions (L2SP, L1SP, L1SCom and L0SCom). L1SCom maps are also useful to guide the on-going trials of *H. scabra* restocking through the release in the field of juveniles grown in nurseries. Targeting habitats where juveniles face greater chances of survival seems critical for the success of such efforts (Bell et al. 2006).

On-going evaluation of conservation measures includes the level of representation of ecosystems and habitats in marine protected areas (MPA). For each habitat, a representation score can be computed from a habitat map to assess what percent of a given habitat surface area is included in MPAs. This index forms, for instance, the basis of the evaluation of the AICHI Biodiversity Target 11 (Wabnitz et al. 2010, Gairin and Andréfouët, 2020). New Caledonia thus far includes seven MPAs in the North Province and 28 in the South Province, with IUCN categories ranging from I to VI. Outside the Provinces' territorial waters, New Caledonia's EEZ constitutes the PNMC, as established by the Government of New Caledonia in 2014. The PNMC includes both IUCN category Ia and II (Fig. 11). The UNESCO areas indiscriminately include zones that are within the spatial domains of the three Provinces as well as within the PNMC, therefore resulting in possible overlap with existing MPAs. Considering the complex governance of New Caledonia, the L0SCom map product was used to estimate the representation of seagrass bed in the six UNESCO clusters and within the 35 MPAs that can be considered as managed. Results (Table 1) show the low percentage of seagrass representation in MPAs (4.4% of all communities). Percentage of representation in the UNESCO areas are more satisfactory (28-46%). Future assessments may wish to include more details on community conservation through L1SCom maps, or on species representation by type of MPA through the L0SCom, L1SCom and L2SP products.

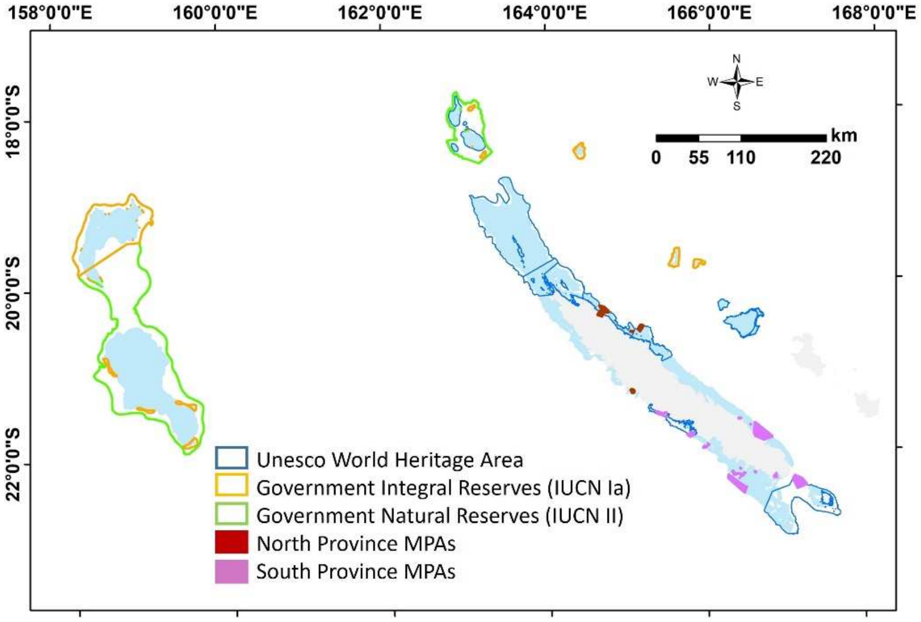

Figure 11: The complex network of MPAs in New Caledonia, which is managed by different political and governance entities (Provinces, Government). UNESCO areas (in six clusters) still lack specific zoning plans, except for the Entrecasteaux cluster, which is managed by the government. Note that several provincial MPAs are included in the UNESCO areas.

Table 1: Representation of the L0SCom seagrass communities in the UNESCO areas, and in the gazetted marine protected areas of the North and South Provinces. Percentages in parentheses are provided relative to the total surface area of each community.

L0SCom community	Total area km^2	UNESCO km^2	MPA (South) km^2	MPA (North) km^2	all MPAs km^2
Dense	126.80	36.30 (28.6%)	2.86 (2.2%)	0.25 (0.2%)	3.11 (2.4%)
Medium Dense	229.99	106.92 (46.4%)	5.95 (2.6%)	6.52 (2.8%)	12.46(5.4%)
Shallow Envelop	585.76	220.04 (37.6%)	16.54 (2.8%)	9.37 (1.6%)	25.92 (4.4%)

4.3 Complementarities with other frameworks

Three conceptual frameworks have recently been proposed to enhance seagrass knowledge and conservation (Unsworth et al. 2015, Duffy et al. 2019, McKenzie et al. 2020). They were global in scope, unlike the scheme proposed here that targets national scales, but which could be replicated in different countries. Sticking to national limits means that political decisions to apply the framework can conveniently remain within the scope of national and local stakeholders, without going through international coordination, which is time consuming in practice. The complementarities between the present framework and previous conceptualizations are briefly discussed.

First, Unsworth et al. (2015) reviewed the principles for the better management of seagrass beds to support their resilience globally. Their conceptual model emphasized the processes responsible for ecosystem shifts and seagrass loss, and the actions required to avoid them. The link to hierarchical multi-scale products and the role of remote sensing for community mapping (L1SCom, L0SCom) are not explicit. However, the products presented here are the necessary foundation of the Unsworth et al. (2015) framework. An important aspect developed by Unsworth et al. (2015), but not explicitly addressed here, is the monitoring of changes, with temporal iterations of products for individual sites across (re)visits, in particular at the L2SCom levels, providing the very foundation needed for the practitioners in Unsworth et al. (2015)'s model. The timing of the revisits should be constrained by the processes (degradation-recovery) that are described by Unsworth et al. (2015) and a series of suitable environmental indicators (Van Wynsberge et al. 2013, Kerninon et al. 2021).

Second, in the context of applying remote sensing more widely to monitor benthic and pelagic macrophytes (macroalgae and seagrass) Duffy et al. (2019) calls for a coordinated global network that would link *in situ* ground-truthing on a fairly frequent basis (ideally seasonal to yearly scale) with remote sensing products. The importance afforded by the authors to ground-truthing of remotely sensed products is in line with our framework. Duffy et al. (2019) do not explicitly address issues of scales and products, although references are given to the 'three-tiers' of Neckles et al. (2012), who describe a quantitative hierarchical framework, but which was applied only within what would be our level 1 site-scale. Duffy et al. (2019) also discuss the relevance of new emerging technologies to map benthic and pelagic macrophytes. However, many are unlikely to be implemented in developing countries. Nevertheless, *in situ* and mapping data similar to that collected and compiled for New Caledonia could contribute to the network advocated by Duffy et al. (2019).

Finally, McKenzie et al. (2020) describe a niche modelling exercise to estimate the extent of seagrass globally. While we do not recommend employing a modelling approach for such an objective if remote sensing observations are available (Andréfouët and Bionaz 2021), we recognise that the frequent presence of seagrass in turbid, or optically deep, areas impairs a global assessment relying entirely on remote sensing and that models can also provide some information for fieldwork stratification. Further, the authors critically compare the model output with existing national data and mapping products, although they stumble against significant gaps for most countries. Hence, they logically discuss the gap-filling input that remote sensing can provide in shallow areas although the scales are not as formalized as here, the range of suggested image processing methods are different than what we recommend and have applied in New Caledonia, and they don't mention a stratification that could be initiated from a L0R reef/lagoon mapping product. The equivalent of the L0R product would be the output of the seagrass modelling product. They also point to the role that citizen science can play in providing information, an approach not discussed here, but which could be implemented considering the successes of these participatory initiatives in New Caledonia (Derville et al. 2018, Dumas et al. 2020).

4.4 Changes in seagrass beds and the extension of the framework for monitoring

The framework presented in Figure 2 and used in New Caledonia does not have an explicit temporal component. It assumes seagrass community stability, while conversely, natural dynamics are explicit in Unsworth et al.'s (2015) framework to assess seagrass resilience. Our temporal observations across a few meadows in New Caledonia over the course of nearly two decades tend to suggest an overall remarkable stability (or resilience) of the boundaries of these meadows (SA, unpublished data). This however can be subjective as quantitative data are limited. Conversely, we also have evidences, from historical aerial photographs (some from the World War II) and satellite imagery, that seagrass communities have varied widely in extent (sometimes positively) and density at some New Caledonia locations (such as around Noumea, Moindou, Koné, Poé and Isle of Pines; SA, unpublished data, but readers can check locations around New Caledonia in Google Earth ® such as for instance the Kanumera Bay in Ile des Pins). At shorter time-scales (5 years), in the context of mining impacts around the Koné site, Van Wynsberge et al. (2013) suggest seasonal and inter-annual differences in the cover of different seagrass communities. They discuss the significance of the changes and possible management decisions according to different indicators and sampling efforts. Elsewhere in the Indo-Pacific, stability and resilience have been confirmed, like Fiji, despite coastal development and high energy events such as cyclones experienced in the past decade (McKenzie and Yoshida 2020), but reports of seagrass loss directly impacted by developments, global warming and heatwaves are common (Short et al. 2014, Strydom et al. 2020).

To reflect temporal changes, it is possible to extend the framework with multi-year L2SCom/L2SP data, while still having the possibility to compile lower level L1/SP/L1SCom and L0SP/L0SCom products without, or with, a filter on dates of surveys. The information becomes both spatially and temporally explicit in this case. For multi-temporal sites that demonstrate large or small changes in communities, regardless of the community variable (sediment, canopy height, epiphytes, etc.), it is possible to create a new L2SComS succession product that can describe the exact changes and the shifts from one L2SCom community to another. Some shifts could be seasonal or follow different inter-annual variations on a case by case basis.

4.5 Implementation of the framework across and relevance for other Indo-Pacific island countries and territories

In the tropical Pacific Ocean, Melanesia is the region with the highest number of seagrass species, followed by Micronesia and Polynesia (McKenzie et al. 2021a). Moving eastwards across the Pacific, richness appears to decrease drastically: the highest richness is reported in Papua New Guinea (13 species), while the Cook Islands, Nauru, Niue, Pitcairn Islands, and Tuvalu seem devoid of seagrass. To our knowledge, a similar recent regional update and synthesis exists for Asia (Fortes et al. 2018) but not yet for the Indian Ocean. Large islands, like Madagascar, and the Coral Triangle Area are likely to present high national richness and numerous local configurations of interest.

All Indo-Pacific countries have already developed some of the framework components presented herein. Specifically, all Indian and Pacific Ocean island countries have a L0R MCRMP product. All countries with seagrass also have benefited from some type of L2SCom or L2SP field survey (McKenzie et al. 2021a,b). What is presently unknown is the representativity of these L2 products, which can be measured retrospectively against an L0R or L1SCom suite of products. L1SCom products specifically targeting seagrass communities and validated through ground-truthing exist for several local sites, including Aldabra (Seychelles), Rodrigues, and Chagos, among others (Hamylton et al; 2012, Pasnin et al. 2016, Esteban et al. 2018). In the Pacific Ocean, besides the New Caledonia sites mentioned, recent seagrass L1SCom mapping work includes for instance Solomon Islands and Fiji (Roelfsema et al. 2013). Satellite images are most commonly used today, but aerial photographs, including from new drone platforms can provide useful information as well. In most of these L1SCom products, however, only density and sometimes the types of substrate are explicit. Nevertheless, we reemphasize that L1SCom mapping products are not mandatory if local expertise does not exist to conduct high resolution mapping with accuracy and if knowledge of species distribution (L0SP or L1SP) is the priority knowledge gap to be filled. However, the collection of *in situ* data should be considered mandatory and represents the foundation of all mapping work, since ground-truthing data is absolutely critical to the production of accurate and high-quality products that can meaningfully inform decision making in conservation and resource management.

4. Conclusion

Through the seagrass inventories and seagrass community maps developed for New Caledonia since 1984, we have implemented a multi-scale hierarchical framework to describe and map a variety of seagrass data sets. The framework may be applied from small to large scales, including archipelagos and entire nations. It is also flexible in the integration of remote sensing products or not. Specifically for New Caledonia, future priority research could include filling outstanding spatial gaps, including for deep lagoonal areas, and further developing research and management programs targeting seagrass-specialist species, such as the dugong or green turtles. Other data sets could be included such as recent surveys around Koumac (GD, unpublished data) and data collected by private companies while undertaking mining impact assessment studies. Further, it would be critical to characterize the functional properties of the main seagrass communities observed around New Caledonia and their differences in term of contributions and services provided to local human communities.

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