SINOPSIS – The Solomon Islands National Ocean Planning Spatial Information System: Spatial decision support tools for seaweed aquaculture planning in the Solomon Islands

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Abstract

Seaweed cultivation can provide important income in remote areas and significant exports for nations like the Solomon Islands. It may also provide a sustainable alternative to more extractive industries like forestry, fishing and terrestrial agriculture. This report outlines the spatial decision support tools developed to help planners and policy makers in the Solomon Islands identify sites suitable for seaweed cultivation. In collaboration with the Solomon Island Ministry of Fisheries and Marine Resources we identified physical, biological, economic and social factors influencing the suitability of locations for seaweed farms and mapped 35 existing, previous or potential locations for seaweed farms.

We integrated data from physical and biological surveys with population census data and suitability scores rated by seaweed farming experts familiar with the region. The open source geographic information system QGIS was used to map over 100 variables approximating suitability for seaweed farming in terms of marine habitat, distance to land, rivers, transport, and protected areas and possible social and economic constraints. Data were georeferenced to point locations for known seaweed farming areas and to habitat polygons for reefs throughout the Solomon Islands. Multivariate patterns among farm sites were analysed and mapped and a hierarchical multiple criteria model was used to estimate site suitability according to standardised site scores and weighted criteria. We used high-resolution satellite imagery to map seaweed farms near Wagina Island at two times, and photos from unmanned aerial vehicles (UAV drones) to build georeferenced photo-mosaics at five sites in the Western Province.

Findings from the project include that: 1) potentially suitable environments for seaweed farms can be identified from GIS habitat maps produced for the “Millennium Coral Reef Mapping Project” (Institute for Marine Remote Sensing, University of South Florida (IMaRS-USF), 2005); 2) suitability was also affected by depth, substrata, current, wind and wave action and herbivory by fish, dugong and turtles; 3) the market price of seaweed, buying arrangements and competing opportunities for employment in other industries were important economic and social constraints; 4) surprisingly, distances to the capital city, towns, villages and land appeared less important in an archipelago linked by networks of coastal waterways; 5) while existing databases illustrated broad patterns in factors affecting suitability, there were subtleties in human judgement and interpretation that were not easily captured using GIS data alone; and therefore 6) an interactive exploratory approach combining data and local expertise is likely to be more successful; 7) drone photography and

online satellite imagery can be used to map farming areas at different spatial and temporal resolutions; and 8) GIS can spatially integrate diverse data sources and interactive modelling tools within intuitive visual analyses.

Table of Contents

List of Figures

1 Introduction

This project developed geographical information system (GIS) decision support tools to help plan for sustainable development of seaweed farming in the Solomon Islands. Seaweed farming across the Pacific has grown considerably in the last few decades (Zemke-White and Ohno, 1999, Zemke-White and Wilson, 2015) but there are significant bottlenecks to development including the ability to keep track of existing farms and to identify suitable locations for farms (MRAG Asia Pacific, 2016).

Seaweed farming trials began in the Solomon Islands (Figure 1) in 1988 with cooperation from the MFMR (Ministry of Fisheries and Marine Resources) in the Western Province at Vonavona Lagoon and Rarumana Village. The trials imported the red alga *Kappaphycus alvarezii* from Fiji and demonstrated good production. Unfortunately, herbivorous fish affected most of the trials. In 2001, the Aquaculture Division of MFMR began trials in Rarumana. The following year, trials in Rarumana produced over 600 kg of seaweed (dry weight). The RFEP (Rural Fishing Enterprise Project) held seaweed farming workshops in cooperation with the MFMR and SPC (Secretariat of the Pacific Community) and in 2003, RFEP provided materials for seaweed farming, including outboard motors, internet for communication and a warehouse in Rarumana.

In 2005, there were around 130 seaweed farmers in Rarumana and the Shortland Islands, and 300 seaweed farmers in Wagina. Farming then expanded to Makira-Ulawa and Malaita. Operations also began in eastern Marovo Lagoon. A year later, the prices for seaweed fell by 20 % due to the increase in fuel prices which also affected national and international freight costs. In 2007, natural catastrophes resulted in the loss of seaweed farms in Rarumana, where they remain out of operation, although farming continues at Wagina and some other smaller areas.

Seaweed farming is a practice that does not require extensive investment and technology, and it may not impact heavily on the environment. However, the industry in the Solomon Islands, is constrained by finding suitable sites and maintaining employment consistency, production rates and market accessibility.

One of the advantages in farming *K. alvarezii* is its vegetative reproduction. It is a clonal species which can be propagated through fragmentation (Hurtado et al., 2014; Buschmann et al., 2017). The farming process is also considered relatively simple with low capital costs, and quick production cycles, and it has become a favourable practice among coastal communities (Valderrama et al., 2013; Kumar et al., 2015; Mantri et al., 2016).

Countries in the Pacific usually practise the off-bottom, floating-raft and floating longline methods (Pickering, 2006). In Asia, the shallow off-bottom mono-line technique is one of the most popular methods used in recent times (Hurtado et al., 2013). Trono (1992) and McHugh (2006) provide descriptions of this and other farming techniques.

The off-bottom longline method involves straight rows of wooden stakes driven into the substratum and connected by 3 mm propylene line suspended approximately 30 cm above the seafloor (Msuya, 2006). Small cuttings of seaweed are attached at 20 cm intervals on the propylene lines using raffia tie-ties. This is the main form of seaweed farming in the Solomon Islands currently. Floating long lines, where seaweeds are suspended just below the surface, have also been trialled in the Solomon Islands and are less dependent on depth and substrata.

According to Glenn and Doty (1990), one of the main hindrances to developing seaweed farming is finding productive sites. As part of this project, Vavia (2018) used GIS software to integrate environmental, social and geographical data to identify potential sites for seaweed farming in the Solomon Islands. This project builds on the above study with data and software that allow Solomon Island Fisheries staff to view and analyse data for different environmental and socio-economic criteria and their effect on site suitability.

The Solomon Islands National Ocean Planning Spatial Information System (SINOPSIS) project had two primary objectives. The first was to create decision support tools to allow managers and other stakeholders to plan for sustainable development in seaweed farming. The second was to build capacity and training in the use of GIS-based decision support tools and remote sensing.

The starting point for the research was a socio-economic review of a 3-year seaweed aquaculture project undertaken by the consultants MRAG Asia Pacific funded under the New Zealand Aid Programme's (NZAP) Mekem Strong Solomon Islands Fisheries (MSSIF) programme. The review analysed the socio-economic outcomes for the Solomon Islands as a result of MSSIF funding and made six recommendations, four of which are germane to this project. Firstly, continue aid funding, as it has been shown to be effective and critical to the development of the seaweed industry.

Second, conduct a census seaweed farms, as the poor temporal resolution of farm statistics produces uncertainties in the value of the industry to the economy and may also impact on effective disaster relief. This project therefore, provides training and geospatial mapping tools that enable Ministry of Fisheries and Marine Resources staff to assess farm areas more frequently.

Third, improve methods to identify new growing areas. The project integrates GIS, analytical tools and spatial data to enable government managers, scientists, industry and communities to visualise physical, biological and socio-economic influences on farm site suitability and compare suitability scores for different locations, scenarios and priorities. The tools integrate GIS data from many sources with heuristic knowledge from expert opinion.

Finally, geospatial analyses can be used to proactively plan for sustainable development and avoid issues resulting from expansion and competition. The GIS databases and tools include information on ecologically important habitats such as seagrass, mangrove and coral reef, on marine protected areas and on the distribution of villages, population, transport and infrastructure. The distance from farm sites to such features can be weighted in models to reflect negative or positive contributions to farm site suitability. The models allow managers and stakeholders to visualise spatial relationships between farm sites and surrounding habitats and human activities and interactively explore potential management options and outcomes.

In planning this project, we consulted with Solomon Island Government managers, field staff, consultants and local people (Appendix 1). In particular, two staff members of the Solomon Island Ministry of Fisheries and Marine Resources (MFMR) and consultants worked on the team providing expert local knowledge of seaweed farming in the region and input into the design of the decision support tools.

Three young Pacific researchers were investigators on our project. Antony Vavia (of Fijian and Cook Island descent) completed his BSc (Hons) dissertation on “Selecting Seaweed Farm Sites in the Solomon Islands using Geospatial Information Systems.” Much of the research presented in this report is drawn from Antony’s dissertation. Clayton Chan (from Samoa) completed a research project on “Using Remote Sensing Technology to Analyse Land Use Change in Vavanga, Solomon Islands.” Jillian Fenigolo was cultural liaison and research assistant on the ethnographic investigations led by Prof. Richard Walter from Otago University.

We initially engaged in workshops with staff and students at the Solomon Islands National University (SINU) and staff at MFMR, MSSIF and the Solomon Islands Government Information, Communications and Technology Support Unit (ICTSU) on the use of remote-sensing technologies and GIS-based decision support tools. Additional training occurred on field trips with Ministry of Fisheries and Marine Resources staff and later at a 3-day workshop with approximately 15 staff, consultants and students.

Consultation with managers, industry and scientists were used to refine project objectives and identify criteria to select areas suitable for seaweed farming. These objectives and criteria were used to identify and acquire data sets and tools best suited to site selection. Ideally, existing GIS data sets were sourced but other remote-sensing data, non-spatial data, literature and anecdotal information were collated and converted to spatial formats where possible. Environmental and other geospatial constraints were formally summarised within multiple criteria models providing a basis for quantitative and qualitative comparisons among sites. Proximity analyses of distances, transport links and access between farms, coastal populations and markets were used to evaluate logistic feasibility for local and regional infrastructure, development, production and the transport of goods and employees.

There is a wide range of geospatial analysis tools that can be used to help select or prioritise areas. We aimed to develop tools that could be easily and cheaply used and applied generally to similar projects in other areas. These include spatially explicit, graphic, interactive GIS displays particularly suited to community participation in meetings, promoting public awareness and incorporating local knowledge and opinion. Where necessary, we used spatial modelling, multivariate statistics, and multiple criteria analysis to help identify potential farming locations. Multiple criteria analysis evaluates the performance of a set of options in meeting an overall goal in terms of sets of weighted objectives and criteria. In this project, multiple criteria analysis was used to combine data for many parameters and sources in an interactive model that can be used to rate alternatives according to existing data and expert opinion. In line with review objectives, we trialled the use of satellite and drone imagery to map and census seaweed farms and ground-truthed some locations using underwater video transects. Under increasing aquaculture development, it will become increasingly important to monitor the growth of the industry, its impact on surrounding areas and the potential for conflict with competing use. Remote-sensing tools can assist in this work.

All formatted data, software, analyses and a dedicated laptop computer were provided to the Solomon Islands Ministry of Fisheries and Marine Resources with a DJI Phantom 4 drone and training to allow Fisheries staff to map farm locations.

The following sections describe the methods used to incorporate expert knowledge on seaweed farming in the Solomon Islands, define criteria for site suitability and display and analyse data in a Quantum GIS (QGIS) project application and in multivariate and multiple criteria analyses. A results section displays examples of maps and quantitative analyses of seaweed farm-site suitability according to expert ratings, environmental data and analyses. Finally, we discuss the implications of the project outcomes and make recommendations for future research and management.

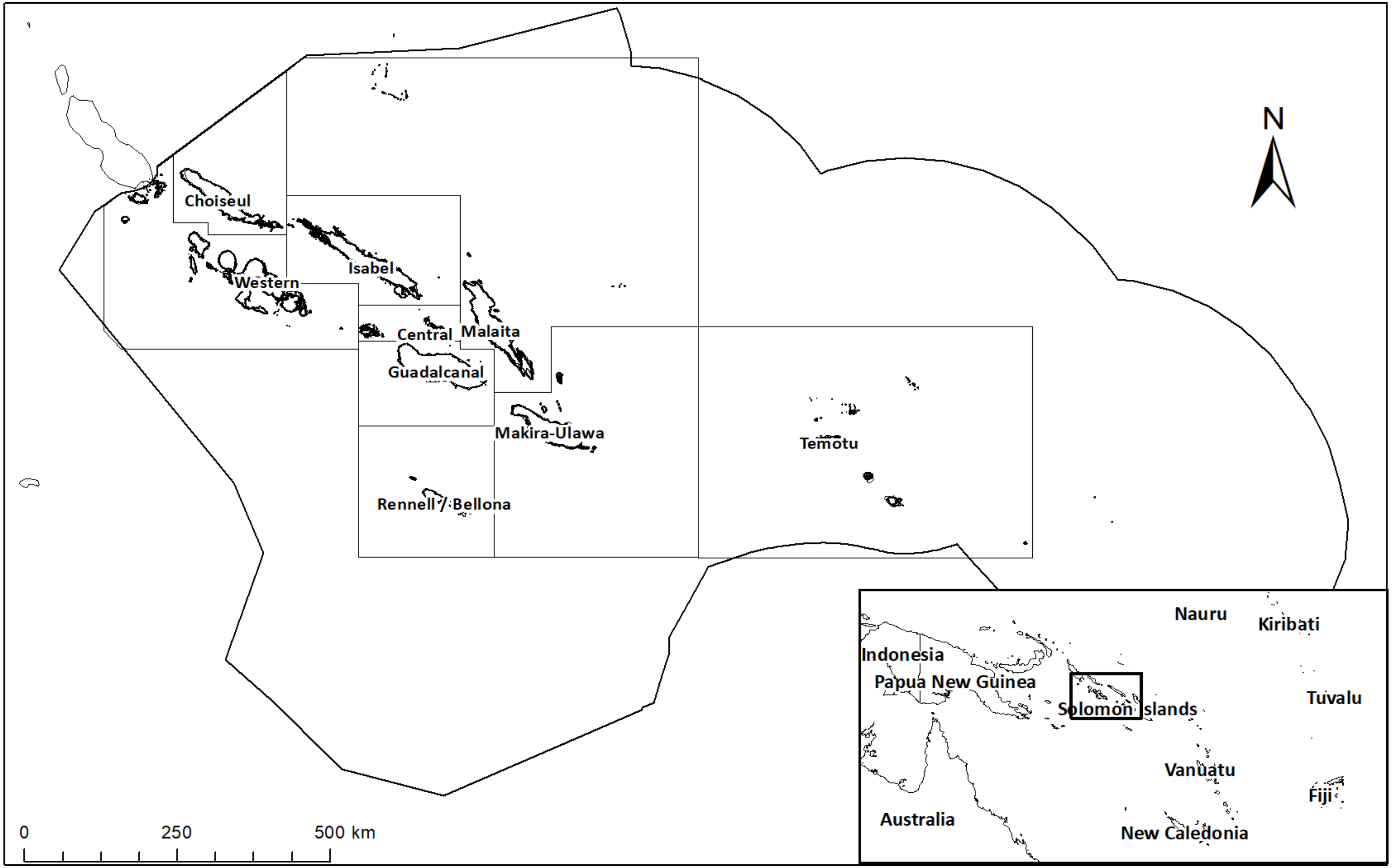

Figure 1. Location of the Solomon Islands and the Exclusive Economic Zone.

2 Methods

2.1 Location

The project was based in the Solomon Islands, which lie east of Papua New Guinea (Figure 1). The Solomon Islands include nine provinces: Choiseul, Western Province, Isabel, Guadalcanal, Rennell/Bellona, Central, Malaita, Makira-Ulawa and Temotu and have an exclusive economic zone of around 1,600,000km^2.

Consultation occurred primarily with government and university staff in the capital city of Honiara on the island of Guadalcanal but also around Gizo in the Western Province where field surveys of existing, previous and potential seaweed farm sites were made.

2.2 Expert knowledge

Criteria for seaweed farm sites were identified from previous studies (Glenn and Doty, 1992; Trono, 1990, 1992; Msuya, 2006; Sousa et al. 2012; Dean and Salim, 2013; Kapetsky et al. 2013; Cabral et al. 2016) and from discussions with fisheries staff, consultants and community. A manager, GIS officer and a consultant for the Ministry of Fisheries and Marine Resources worked with Auckland University of Technology (AUT) staff and students to map the approximate boundaries of existing, previous and potential other sites for seaweed farms (Figure 2). They also rated the suitability of the 35 sites for farming (on a scale from 1, least suitable, to 10, most suitable) for 20 potentially influential variables and for each site's overall suitability. The relative importance of each variable for seaweed farming was also estimated on a scale from 1 to 10.

This information was mapped, included in the decision support tool and analysed in multivariate ordinations, cluster analyses and multiple criteria analysis as described below. Correlations between information sources, managers and multiple criteria scores were examined graphically and by Pearson's r statistic.

2.3 Site selection criteria for seaweed farms

Physical, biological, social and economic variables likely to affect the suitability of locations for seaweed farming were identified from literature and from discussions with the Solomon Islands Ministry of Fisheries and Marine Resources staff and consultants. These were refined during discussions with managers, consultants and stakeholders, rated according to their importance in general, and for specific farm sites, approximated in spatial GIS analyses and incorporated into GIS displays, multivariate analyses and multiple criteria analysis.

Under different conditions, many ecological and social parameters may impact on site suitability and there may be no hard and fast rules for predicting the success or impacts of farming. The decision support tools developed here are designed to be flexible to allow a wide range of possibilities to be considered by making information readily available in an intuitive geographic format.

2.3.1 Physical selection criteria

Depth

For the off-bottom longline seaweed farming technique, water depth is critical. At the lowest tides, the seaweed should remain covered with water, but it should be shallow enough for workers to wade among and access the lines easily. Broad-scale bathymetry data within reef areas were of relatively low resolution. However, specific habitat types (shallow terrace) classified by the Millennium Coral Reef Mapping Project (IMaRS-USF, 2005) from satellite data provided a useful representation for factors such as depths, substrata and shelter from ocean swell in areas most likely to support off-bottom seaweed farming. This report focuses on site selection for the off-bottom method but the data and tools could also be used to explore the potential for other farming methods.

Tidal range

Tides naturally vary within and between months of the year but the highest spring tides at most stations in the Solomon Islands are only 1–2 m (Sulu et al., 2000; https://www.tide-forecast.com/locations/Wagina-Island-Solomon-Islands/tides/latest) which is small relative to other regions and to the depths best suited for the off-bottom technique.

Temperature

Sea temperature can influence the growth rate of seaweeds, cause stress in the cultivar and may encourage the growth of competitive algae. Temperature varies throughout complex reef lagoon systems and in response to currents, wind and weather and is therefore difficult to map at scales relevant to the location of individual farms. In GIS proximity analyses, we estimated the distance of habitats and farm sites to the reef crest and open ocean as an approximate indicator of water movement and its effect on temperature and other water properties.

Freshwater
Seaweeds (especially *K. alvarezii*) are adversely affected by low salinity from rivers and streams, runoff from the coast itself and even heavy rainfall during low tides. Turbidity associated with freshwater runoff also affects the transparency of sea water and this can impact on photosynthesis. We used distance to land and distance to the nearest river mouth to indicate the potential influence of freshwater on farm suitability.

Ocean swell
Large waves, especially from oceanic swells, exclude seaweed farming in its current form from locations near reef fronts and passes. The sheltered shallow terrace habitats mapped in the Millennium Coral Reef Mapping Project are generally protected from most ocean swells. Impacts from rare but catastrophic events like cyclones and tsunamis are less predictable.

Current
Strong currents may damage seaweed farm structures and the plants themselves, but low to moderate flows appear to benefit seaweed growth. Backwater areas of enclosed lagoons with minimal water exchange are not recommended for farming. Glenn and Doty (1990) observed that downstream seaweeds were unhealthier than those upstream, tended to have less colour and were more fragmented because of the disease, "ice-ice." Mtolera (2003) showed that the growth rate of *K. alvarezii* can be heavily impacted by the presence (or absence) of minerals such as Cu, Fe, Mn and Zn (Glenn and Doty, 1992). Similar observations were made by Hurtado et al. (2014) on intensive farming conditions near dense structures and bamboo rafts. Distance from reef crest and the open ocean provided a very coarse indicator of water movement but expert judgement, field surveys, and aerial photos and habitat maps can also provide an indication of current strength and direction.

Wind
Msuya (2006) stated that strong winds can break and wash away seaweed resulting in large losses for seaweed farms. This also means that farmers must spend time and resources fixing the farms and replanting the seaweed.

Substrata
Sandy areas without boulders are preferred for the stakes used in the off-bottom method. The shallow terrace habitat mapped by the Millennium Coral Reef Mapping Project (IMaRS-USF, 2005) appears to include mostly sandy substrata but may also include rocks above and below the surface. This habitat tends to be located inshore of the reef flat, on the edge of lagoons where the deposition of sand is more likely.

Natural disasters

A major risk for seaweed farming is natural catastrophes such as earthquakes, tsunamis and cyclones. An example from the Solomon Islands is the 2007 tsunami that devastated the Rarumana seaweed farms. Other concerns are increasingly high sea temperatures, prolonged precipitation and the effect of strong currents and ocean swells. In near-shore areas, rivers and runoff from land can cause seaweed to become stressed. Rain also interrupts the drying process and may cause seaweed to disintegrate (McHugh, 2002, 2003, 2006). While these issues cannot be controlled, they may be anticipated, and risk built into the assessment of areas where seaweed farms might be developed.

2.3.2 Biological selection criteria

While abiotic parameters including temperature, light, pH and salinity are important factors that influence the distribution and growth of seaweeds (Borlongan et al., 2016), biotic factors such as algal disease, grazing fish and competitive algae (epibionts) affect the development and productivity of seaweed farms as well as the quality of the products (Buschmann et al., 2017).

Competition with other algae

Epiphytes compete with host organisms for dissolved inorganic carbon and nutrients (Borlongan et al., 2016). Infected *K. alvarezii* can have lower photosynthetic rates compared to healthy seaweed, particularly when epiphytes cover a large surface area (Hurtado et al., 2014). Macro-epiphytic algae incur more labour for seaweed farmers as they must remove epiphytes to maintain the health of the cultivars. Filamentous epiphytes have caused issues for farms in Rarumana and the Shortland Islands and resulted in severe losses. This issue can be managed by placing the seaweed farms in locations where there is better water flow (Kronen, 2013).

Disease

The seaweed industry has suffered from declines in production from a disease known as *ice-ice* (Loureiro et al., 2009, 2015) caused by ecological stress (unfavourable water temperature, pH, salinity changes, high irradiances or UV radiation) (Kronen, 2013; Borlongan et al., 2016). Four forms of seaweed disease include:

1. Ice-ice, generally characterised by the white flakes on the thallus of *K. alvarezii*.
2. Pitting, identified by the cavities forming on the branches.
3. Tip darkening, where the end segments of the branches lose colour.
4. Tip discolouration, where the tips become soft and pinkish and dissolve.

Diseased *K. alvarezii* branches demonstrate a decrease in photosynthetic performance, which may reflect the decrease in pigment concentrations (Ganzon-Fortes et al., 1993). Again, the incidence of this problem may be reduced where there is better water flow.

Herbivory by fish, turtles and dugong

Herbivorous fish, such as rabbit fish (family Siganidae), graze heavily in some seaweed farming areas to the extent that is it hard to justify starting a farm (Kronen, 2013). The growth of seaweed can be stunted simply by having the plant tips eaten (Msuya, 2006). Seasonal fish grazing was an issue during trials in the Solomon Islands and could be avoided by moving farms to areas with less grazing (Kronen, 2013). Grazing from turtles and dugongs also causes a loss to production in some areas of the Solomon Islands (pers. com. Wesley Garofe, 2017; McHugh, 2006).

2.3.3 Economic selection criteria

Economic factors such as the costs of inter-island shipping and prices received overseas for seaweed have a major impact on the commercial operation and growth of seaweed farming in the Solomon Islands. Some external influences, such as international seaweed prices, are not particularly affected by site selection, but they can influence the relative importance of domestic costs. We therefore made approximate estimates of site characteristics likely to influence the cost of production at the site level.

Fuel and transport costs

Fuel for outboard and other motors is expensive in remote areas but this may be offset by the proximity of farms to the shore and the use of unpowered canoes. Potential fuel costs were approximated by GIS estimates of the distance from farms to the main islands (coast), to small islands, villages, wharves, airports, the capital city and to significant settlements. After discussions with managers we also estimated the distance to the nearest shipping route as an appropriate indicator of site suitability.

Equipment costs

Equipment costs include costs for lines, drying facilities, vessels and motors. These costs are relatively low when compared to other forms of aquaculture but are significant for initial farm establishment and recovery in low-income communities.

Production size

The potential for a site to reliably supply large quantities of seaweed has economies of scale for transport, buyers and, potentially, drying and even processing facilities.

Maintenance costs

Maintenance of seaweed farms (McHugh, 2006) requires removing any competitive algae, repairing any damage to the lines or stakes and replacing lost seaweed due to grazers, diseases or water action (McHugh, 2006). Sites may vary in their suitability in this regard, with respect to transport of workers, exposure to high wind and waves and susceptibility to disease and nuisance algae.

2.3.4 Social and cultural selection criteria

Namudu and Pickering (2006) found that social criteria were often more important than physical factors for successful farming of *K. alvarezii* in the Pacific Islands. Their survey in Fiji analysed community employment opportunities and the perspectives of seaweed farmers and found that distances between farms, working populations and ports can have important economic and social consequences for communities.

Distance to village

The distance of farms from villages can affect the availability of workers, housing and other facilities such as shops and schools. In some areas, however, workers have moved to temporary accommodation on small islands adjacent to seaweed farms.

Competition with other activities for labour and space

Declines in seaweed prices and delayed payments lead farmers to lose interest (Pickering, 2006) and resort to alternative sources of income that provide more money than farming seaweed, such as fishing. Other examples of competing livelihoods are producing copra, harvesting sea cucumbers and logging. While logging and fishing can create environmental problems, environmental issues may also arise from aquaculture (Ottinger et al., 2016). Seaweed farming and tourism industries may conflict as both activities use shallow coastal areas. Conflict between users may also be increased by the visual impact of either practice (Falconer et al., 2013).

Customary tenure

The customary tenure system in the Solomon Islands governs land ownership and also includes the adjoining sea. Each landowning group has a committee that makes decisions around environmental use and there is a strong sense of attachment to traditional rights passed down through generations of family leaders. Integrating conservation efforts with the values of indigenous communities has sometimes been a challenge because of customary rights (Walter and Hamilton, 2014). However, a study by Hviding (1998), suggests that the customary tenure system is compatible with seaweed farming in the Solomon Islands, although the rules of management, including the traditional leaders' ability to govern resource use, have been found to vary between regions (Aswani and Hamilton, 2004).

Permitting access to resources can be difficult due to overlapping and conflicting management approaches that arise due to the nature of descent and entitlement rights. Seaweed farming in the Solomon Islands is done by families and communities from nearby villages (or distant locations where people reside near the farms temporarily) and they may also hire additional workers if necessary (McHugh, 2006). Neighbours may also deny one another access to resources particularly if they are economically valuable (Aswani and Hamilton, 2004).

2.4 Geographic information system and spatial data

The FAO (2014, 2016) has recommended that GIS based studies be used to facilitate aquaculture development and assist with decision making at a national level (Dean and Salim, 2013). An advantage of using a GIS-based approach is its positive impact on decision making by providing useful, and often freely available, quantitative and qualitative information (Radiarta et al. 2008, 2010). There are many regions with relatively low farming intensities, such the Solomon Islands, that would benefit greatly from planning based on good information and consultation, while there is still the opportunity to do so (Kapetsky et al., 2013).

According to Kapetsky et al. (2007, 2013), spatial analysis applications to assist in aquaculture planning need to incorporate multiple models (environmental, social and economic) and be applicable to broad spatial scales. It is important to define potential sites that may be appropriate for sustainable aquaculture and also have the ability to monitor their development and their effect on environments and communities (Ottinger et al., 2016).

GIS can benefit planning for aquaculture by integrating information for many environmental, economic, social and cultural variables from sources ranging from remote sensing, to fisheries surveys and anecdotal interviews. GIS can display complex data in readily interpretable, highly visual maps. It builds on and integrates knowledge, rather than reinventing databases. It enables more complex analyses, simulations and decision support tools and can be used in interactive, participatory planning with stakeholders, communities, managers and scientists.

Spatially referenced data likely to be representative of these factors were collated, formatted and mapped in the ArcGIS (Environmental Systems Research Institute (ESRI)) and Quantum

GIS (QGIS) geographic information systems within a common coordinate system (Universal Transverse Mercator 57S). These include data on islands, marine habitats, shipping routes, infrastructure, seaweed farms, villages, towns, schools, roads, marine protected areas, marine species and marine vegetation. The open source QGIS software is free for all users and will allow many users to access and manipulate the spatial information.

The GIS project interfaces included approximately 100 GIS layers with formatted legends nested within broad topics for clarity and ease of access. An atlas of predefined layouts at specific locations was built to facilitate data exploration and is included within the QGIS project. The digital maps compiled in this research are intended to assist scientists, stakeholders, managers and communities to assess geographic influences on the suitability of different areas for seaweed farms but will also be of use in other environmental planning and assessment.

2.5 Geospatial analyses

Several national-scale GIS data sets for coral reef habitats, seagrass, mangrove, marine protected areas, seaweed farming areas and provinces were combined using the ArcGIS union function into one combined layer of approximately 30,000 polygons. The ArcGIS "Near" command was then used to estimate the distance between each polygon and the nearest river, island, mainland, road, wharf, shipping route, protected area, mangrove, seagrass meadow, village, town and capital city and include this information in the data set. Boundaries of potential seaweed farm locations were intersected with the IMaRS-USF marine habitat classification map to determine which habitats corresponded most frequently with sites identified by managers as suitable for seaweed farming. A simplified GIS point data version of this dataset was generated for existing, previous or potential seaweed farm sites and attributed with distances to the above features, areas of habitats, multivariate statistics and multiple criteria scores.

2.6 Multivariate analyses

Variables describing the suitability of each site according to each manager and according to distances to geographic features were analysed by principal components analyses (PCA of correlation matrices) and cluster analyses (unweighted pair-group method) based on their Euclidean distances. PCA scores and cluster groups were mapped and the results included within the decision support system. The free paleontological statistical software PAST version 3 (https://folk.uio.no/ohammer/past/) was used for multivariate and correlation analyses.

2.7 Multiple criteria analyses

Multiple criteria analysis has been widely applied in business management and environmental impact assessment (Edwards, 1977; www.infoharvest.com; www.expertchoice.com), with applications also in fisheries (Mardle and Pascoe, 1999) and selecting protected areas (Bakus, 1982; Fernandes, 1996; Rothley, 1997; Guikema and Milke, 1999; Villa et al., 2002; Breen et al., 2002, 2004). The techniques incorporate weighting of multiple criteria, calculation of trade-offs, representation of uncertainty, sensitivity analyses of the relative influence of different criteria, and the ability to combine and assess alternative models, data and sources of opinion.

The simplest is the Simple Multi Attribute Rating Technique (SMART) which evaluates alternatives according to a hierarchical tree of criteria nested within more general objectives under a single, broad goal. Variables describing the suitability of each site according to each manager or through geospatial analysis were included within a single hierarchical SMART model using the software Criterion Decision Plus (Infoharvest Inc). Data were first imported into the exploratory "Brainstorm" window of the software and variables grouped by data source and by theme (physical, biological, economic, social) before generating the quantitative model. Variables rated by seaweed industry managers were weighted in the model according to their perceived importance or influence. The models allow for criteria to be weighted interactively according to alternative priorities. Overall scores of site suitability were graphed and mapped for a few examples; other scenarios can be explored using the software itself.

2.8 Satellite image interpretation, drone photogrammetry and ground surveys

Remote sensing is the process of obtaining information about the earth and its surface by scanning from aircraft, satellites, ships or other remote platforms. Sensors mounted on the satellites or other craft measure electromagnetic energy reflected or emitted by the earth's surface in the form of waves (Dean and Populus, 2013; Dean and Salim, 2013). The readings received from these emissions can be classified or processed into different features due to the objects reflecting different wavelengths back to the sensors. The benefits of this information greatly expand the spatial and temporal scope of many oceanographic and coastal studies that cover areas and time scales unattainable by standard methods of ground-based sampling

(O’Regan, 1996). Observations include oceanography data such as surface temperature, ocean winds, waves, currents, turbidity and primary productivity levels (chlorophyll-a concentration) and bathymetry (Dean and Populus, 2013). With a long-time series of information and data, users can assess seasonal patterns and trends at different periods (daily, weekly, monthly and annually) (Dean and Salim, 2013; Kapetsky et al., 2013).

Satellite images from a range of sources were examined to determine whether seaweed farms could be readily viewed and mapped. Georeferenced tif files captured from the WorldView-2 satellite sensor were imported into ArcGIS and the boundaries of farms visible in the Wagina Island region were mapped to compare locations farmed in 2013 and 2015. A plug-in was installed in the QGIS project interface to allow imagery and other data to be sourced online.

A Phantom 4 DJI Professional drone with a 21-megapixel camera was flown over six locations at an altitude of 50 m capturing RGB colour aerial photographs every 2 seconds along a gridded flight path. The flights were pre-programmed using the flight planning software application MapPilot (Drones Made Easy) running on an Apple iPad Air2. This produced a series of high-resolution aerial photographs with an image overlap of greater than 80 %. The software Pix4D v3.1 was used to georeference, align and convert the series of aerial images into a large high-resolution mosaic for each area by matching several thousand joint features in each overlapping photo. Ortho-mosaics were imported into ArcGIS 10.5.1 for analysis and comparison with WorldView2 satellite imagery provided through ESRI base maps in ArcGIS.

At each of the six sites, a 30-minute visual survey by snorkel of the immediate area was conducted of the seabed to verify the types of substrata and benthos represented in GIS habitat maps and aerial photos. At three sites, a waterproof GoPro Hero 3+ camera was used to record video transects of the seabed and associated benthic organisms. Estimates of percentage cover were made by randomly pausing the video footage and recording the substrata and/or organisms under 10 points marked on the viewing monitor.

3 Results

3.1 Geographic information system

Spatial data and analyses were compiled in a central folder accessible through a customised QGIS project interface. The QGIS project includes approximately 100 layers formatted with legends and nested in folder categories including physical, biological, social and economic vector data, analyses, and satellite, drone and other imagery (Figure 2). It includes data layers mapping existing, previous and potential sites (Figure 3), expert ratings of site suitability, the results of proximity, principal components and multiple criteria analyses and many environmental, economic and social features. We present only a few examples as there are too many layers to be displayed here. Figure 2 shows a snapshot of the QGIS project interface with a few groups and layers open. The group folders for the data layers are designed to collapse and expand, be switched on and off, panned, zoomed, queried and analysed using a diverse suite of geospatial functions. The project and GIS data are held by the Solomon Islands Ministry of Fisheries and Marine Resources and the QGIS software is a freely available GIS with many analytical and geoprocessing capabilities in addition to the standard viewing functions.

A major part of the decision support capability is just having a range of relevant, spatially referenced and formatted data readily accessible in one location. A major advantage of GIS as a decision support tool is that complex data for many locations can be simultaneously displayed in a highly intuitive visual environment. It is a decision support, rather than decision-making tool, as it allows users to freely explore data and different planning scenarios in many ways.

At regional scales, complex environments like the Solomon Island archipelago can be challenging to navigate. The QGIS interface therefore includes “bookmarks” referenced to specific locations of interest (such as potential seaweed farm locations) and preformatted layouts for different locations to print maps for whichever layers users wish to present. The project interface includes a preformatted “atlas” function loaded with sequential print layouts for 35 potential farm sites. The basic data structures also provide a generic platform for many other analyses and software tools.

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3.2 Marine habitats

The IMaRS-USF (2005) Millennium Coral Reefs Mapping project uses a combination of spectral analysis and visual interpretation of satellite images to classify coral reefs and surrounding shallow waters into GIS polygons representing different habitats. The main habitat coinciding with areas identified as suitable for seaweed farming was “shallow terrace” or in a few cases, “shallow terrace with constructions” (Figures 4 and 5). The other areas of reef front, reef flat and lagoon in Figure 5 are artefacts from drawing approximate boundaries around complex reef topography as the drying stony reef flat, exposed reef front and deeper lagoon were considered unsuitable for the off-bottom farming method. Deeper habitats may however, be available for other methods such as floating longlines.

When the reef habitat polygons are displayed over satellite images, the shallow terrace habitat coincides with the many shallow, sandy, internal outer margins of reef lagoons sheltered by the outer stony reef flats and reef fronts. The habitat includes shallow areas that are still deep enough to retain some coverage of water on the lowest spring tides. It is intermediate in depth between the shallow back reef flat and deeper lagoon.

Inspection of 35 potential farm sites overlaid on the IMaRS-USF polygons and satellite images confirms the prevalence of shallow terrace and, in a few cases, shallow terrace with constructions as a substratum with potential for seaweed farming. Other physical, biological, social and economic criteria will also determine how viable farming might be, but the area of shallow terrace provides a reasonable indicator of potential locations.

Figure 4 shows the distribution of shallow terrace habitats throughout the Solomon Islands and Figure 6 shows the total area in square kilometres of shallow terrace in each province. While some areas have more of this habitat than others, there are large areas of shallow terrace around most islands throughout the archipelago. Most of the area is, however, in the Western Province, with the least area in Guadalcanal where the capital Honiara is located.

The distributions of shallow terrace and the other IMaRS-USF marine habitats at potential farm sites are mapped in the Appendix of Vavia (2018) and can be viewed at any scale in the SINOPSIS QGIS project. The QGIS project includes other relevant layers such as surveys of coral reefs (UNEP-WCMC, 2010), seagrasses (McKenzie et al., 2016), mangroves (Green et al., 2006), a high-resolution marine benthic classification from satellite imagery of Roviana Lagoon (Roelfsema et al., 2013) and the locations of marine protected areas and other managed areas (UNEP-WCMC 2016). These and other ecological data are important if the seaweed industry is to be not just successful, but also ecologically sustainable.

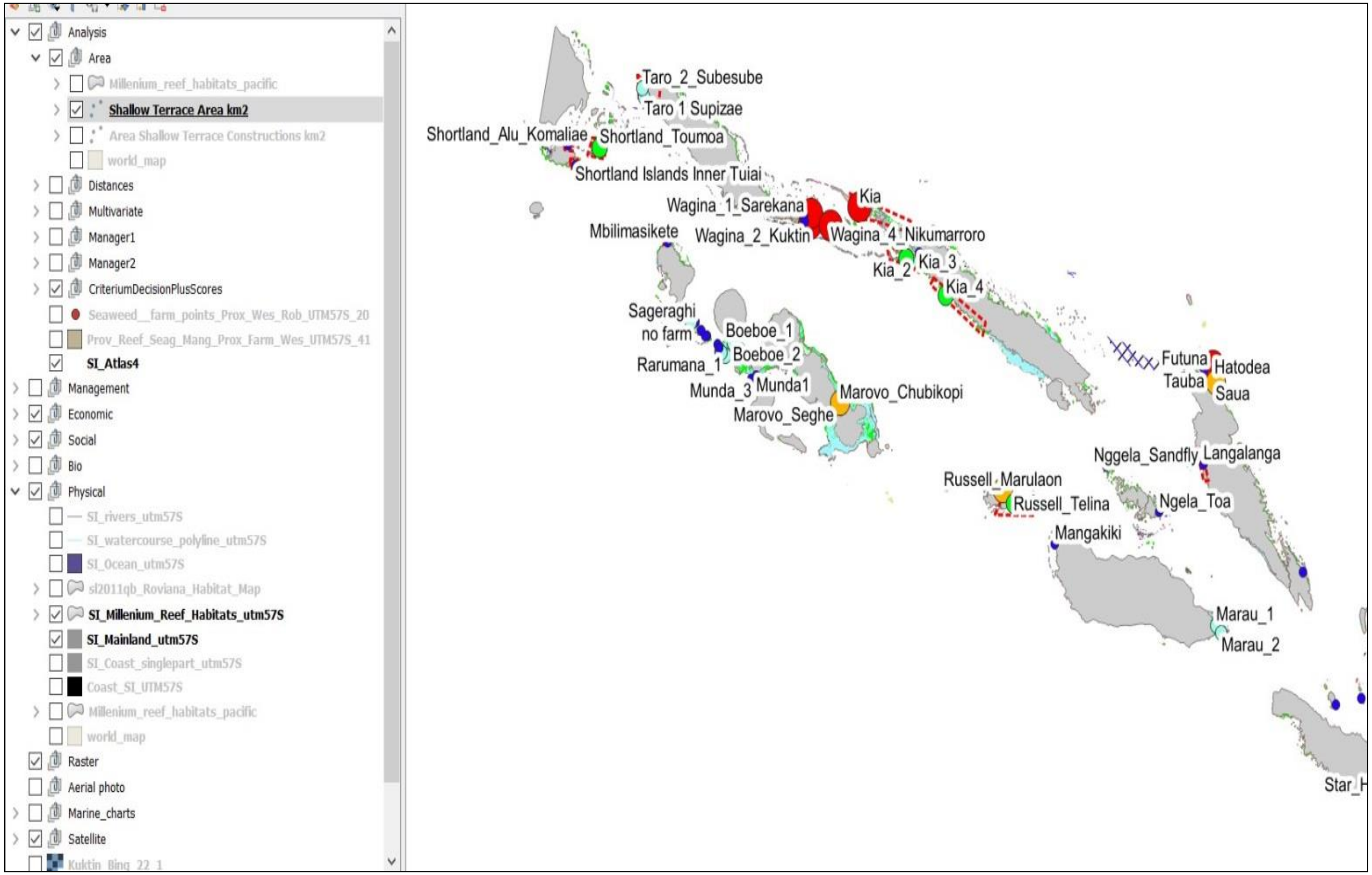

Figure 2. SINOPSIS 3.5 (Solomon Islands National Ocean Planning Spatial Information System). A Quantum GIS 3.2.3 project containing ~100 physical, biological, economic, social and analytical formatted data layers to inform planning for sustainable seaweed aquaculture.

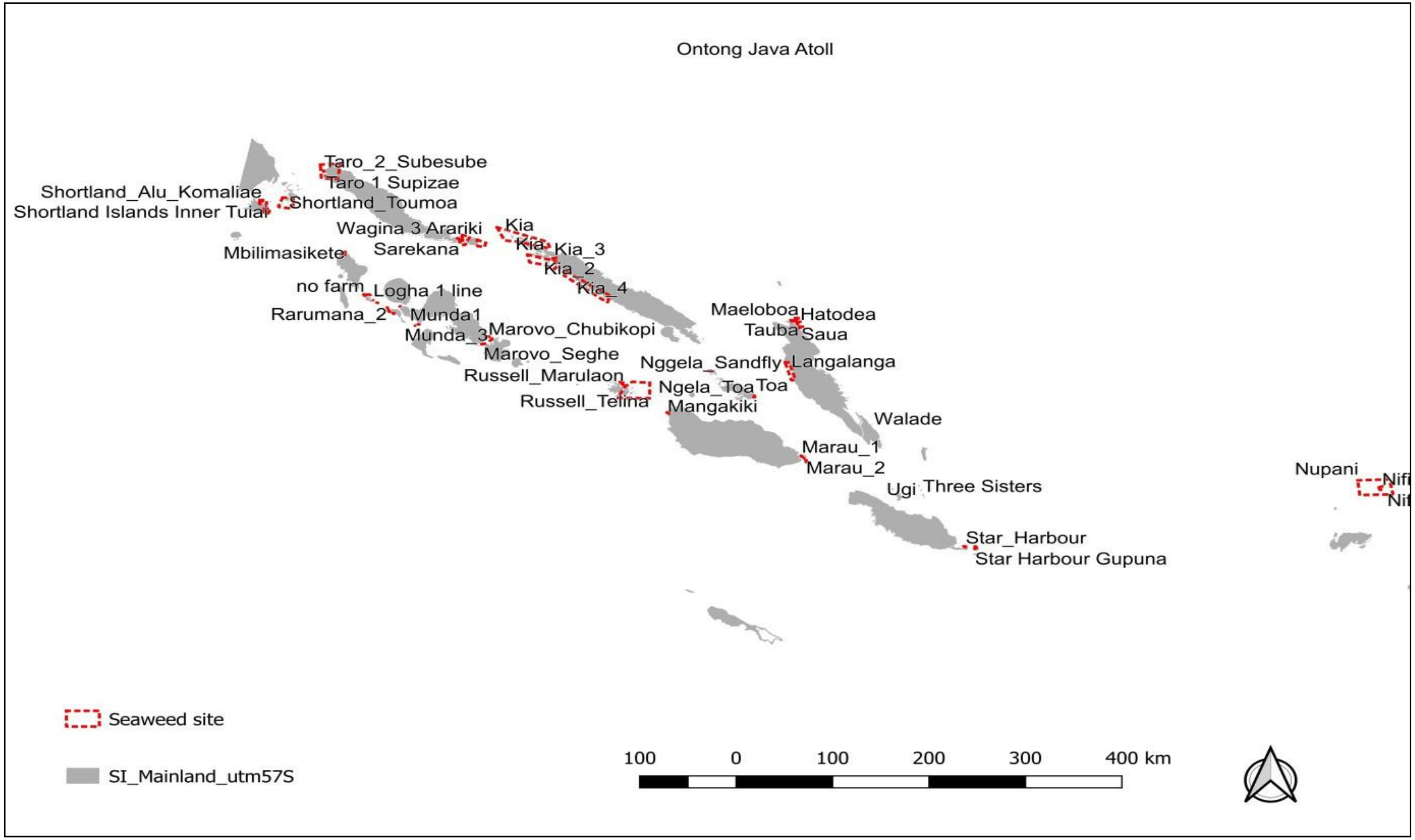

Figure 3. Locations identified as previous, current or potential sites for seaweed farming. These include some sites with marginal conditions which in some way make them less suitable.

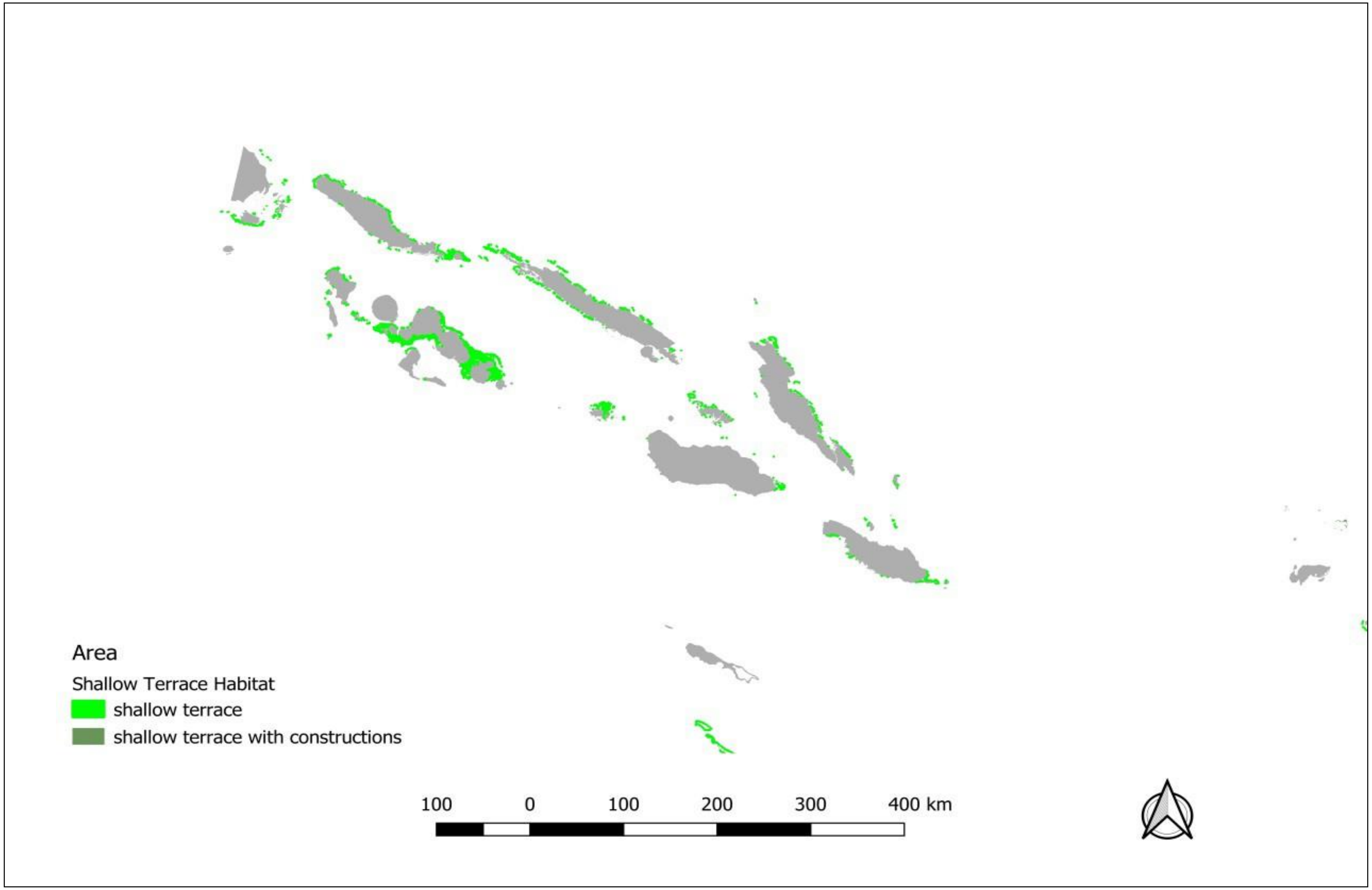

Figure 4. Distribution of "shallow terrace" reef habitats in the Solomon Islands. Data from the Millennium Coral Reef Mapping Project, Remote Sensing Centre, University of Florida. (IMaRS-USF, 2005).

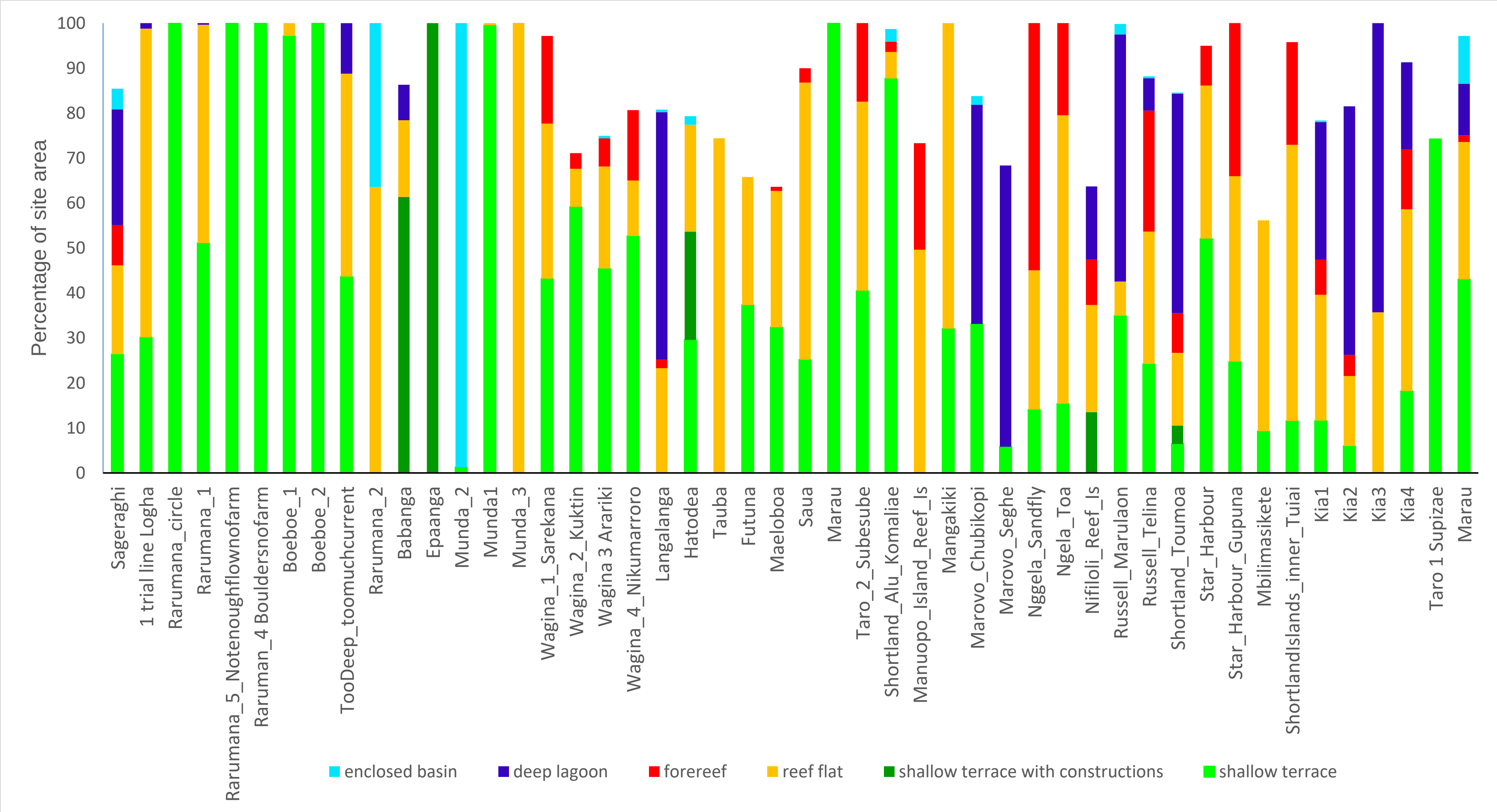

Figure 5. Percentage area of the most common reef habitats at identified seaweed farm locations in the Solomon Islands. Data from the Millennium Coral Reef Mapping Project, Remote Sensing Centre, University of Florida. (IMaRS-USF, 2005).

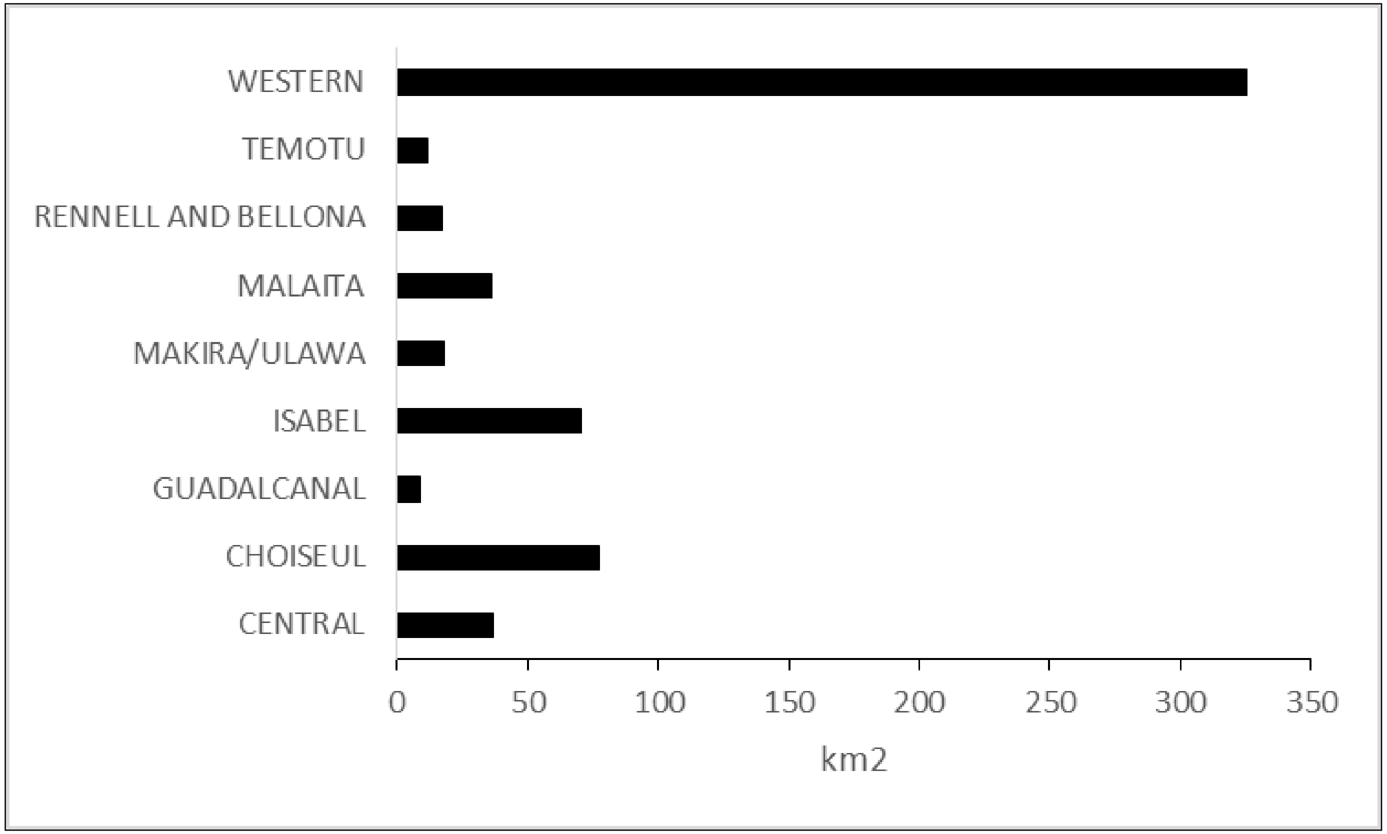

Figure 6. Area of "shallow terrace" marine habitat in provinces of the Solomon Islands. Data from the Millennium Coral Reef Mapping Project, Remote Sensing Centre, University of Florida (IMaRS-USF, 2005).

3.3 Expert knowledge

The approximate outlines of areas identified by managers as existing, past or potential new seaweed farm sites are shown in Figure 3. Figures 7 and 8 map ratings between 1 and 10 (least to most suitable) by each manager for overall suitability as a seaweed farm site. Although several sites, for example around Wagina Island and northern Kia, stand out for their high scores, there are many other locations also highly rated. Not all sites were familiar to both managers, but where a site could be rated by both managers, there was a strong positive correlation between the two managers' ratings of site suitability (Figure 9).

Figures 10 and 11 are multivariate principal components ordinations of each manager's scores for seaweed farm suitability. The ordinations aim to graphically summarise differences among potential farm sites across all expert environmental, social and economic ratings on just two axes. In these examples, the first and second principal component axes explain about 50 % of the variance in ratings. Sites that lie close together on the ordination are more similar across most ratings, while sites further apart are the most different.

The biplots also indicate which variables are most responsible for the differences between sites according to the length and direction of the labelled lines radiating from the centre of the graph. The length of the line indicates the strength of the correlation with the principal component axes and how much variation is explained by that variable.

In Figure 10, in the top right-hand quadrant for Manager 1, sites at Wagina, Hatodea, Ferafaalu and Munda score highly for overall suitability, tidal range, effect of freshwater, current, wind and swell, while only a few sites in the lower left-hand quadrant, Mangakiki, Marau, Toa and Seghe score low on these variables.

On the left, Telina, Sandfly, Supasizae, Star Harbour, Shortland Islands and the Reef Islands score successively higher scores for having less competition in the labour market from competing industries like logging and fisheries but lower for catastrophic disturbance and distance to Honiara. Babanga, Epaanga, Sageraghi, Futuna, Boe Boe and Langalanga score highly on the catastrophic disturbance and distance to Honiara variables. Boe Boe, Langalanga, Chubikopi, Marovo, Epaanga and Babanga also score highly for distance to village and cost of fuel.

At the top of Figure 10, Kia, Marulaon and the four Wagina sites score highest for depth, tidal range, production and overall suitability. In the ordination for Manager 2 (Figure 11), variables rated for overall suitability, substrata, depth and fuel costs explained most differences between sites with Wagina, the Reef Islands, Kia, Hatodea, Marulaon and Sageraghi scoring highest for these variables. Babanga, Chubikopi, Epaanga, Rarumana 1, Star Harbour and Futuna rated lowest on these variables.

Tauba, Star Harbour, Futuna, Marulaon, Sageraghi and Rarumana 2 scored highest on distance to village and distance to drying facilities while the Wagina sites scored lowest on these variables but highest for lack of competition from competing industries. Note that the differences between managers in the absolute positions of variables and sites in the ordinations are an artefact and it is the relative relationships among sites and associated variables that are relevant.

A cluster analysis of multivariate similarity among sites in Figure 12 and Figure 14 for Manager 1 groups similar sites into four clusters. Cluster 1 includes sites at Wagina, and the Western Province, Cluster 2 includes many sites closer to Honiara and Cluster 3 includes more remote small island locations in Kia, the Shortland Islands, Northern Choiseul, Star Harbour, the Reef Islands and small islands closer to Honiara. Cluster 4 is a trial floating line site at Boe Boe.

The cluster analysis of similarity among sites for Manager 2 in Figures 13 and 15 shows five clusters. Cluster 1 is around Wagina Island. Cluster 2 includes Kia, Sandfly, Reef Islands and Sageraghi. Cluster 3 includes most of remaining locations except for Rarumana 1 and Chubikopi in Cluster 4 and Babanga in Cluster 5.

With some exceptions, ordinations for both managers showed similar groupings of sites distinguished by perceived depth, substrata, fuel costs and competition for workers. Some grouping of these sites in geographic space was also evident (Figures 12 and 13).

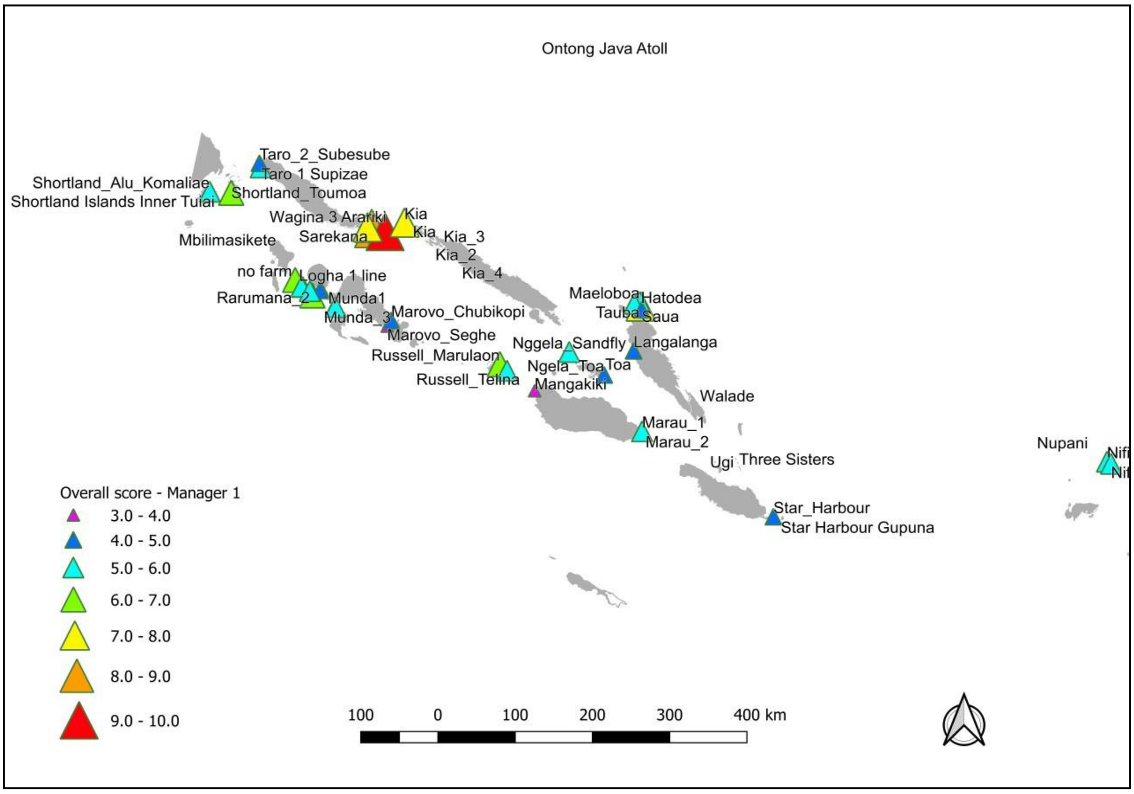

Figure 7. Overall suitability of identified sites for seaweed farming rated by Manager 1.

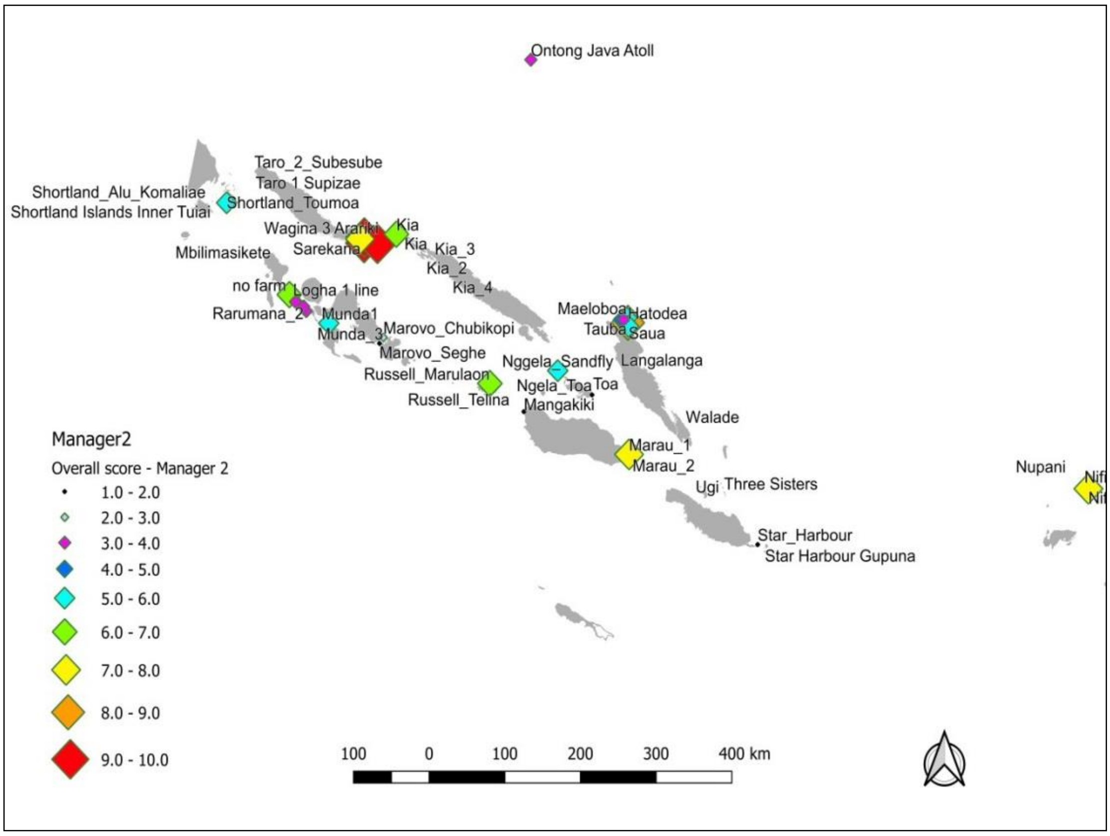

Figure 8. Overall suitability of identified sites for seaweed farming rated by Manager 2.

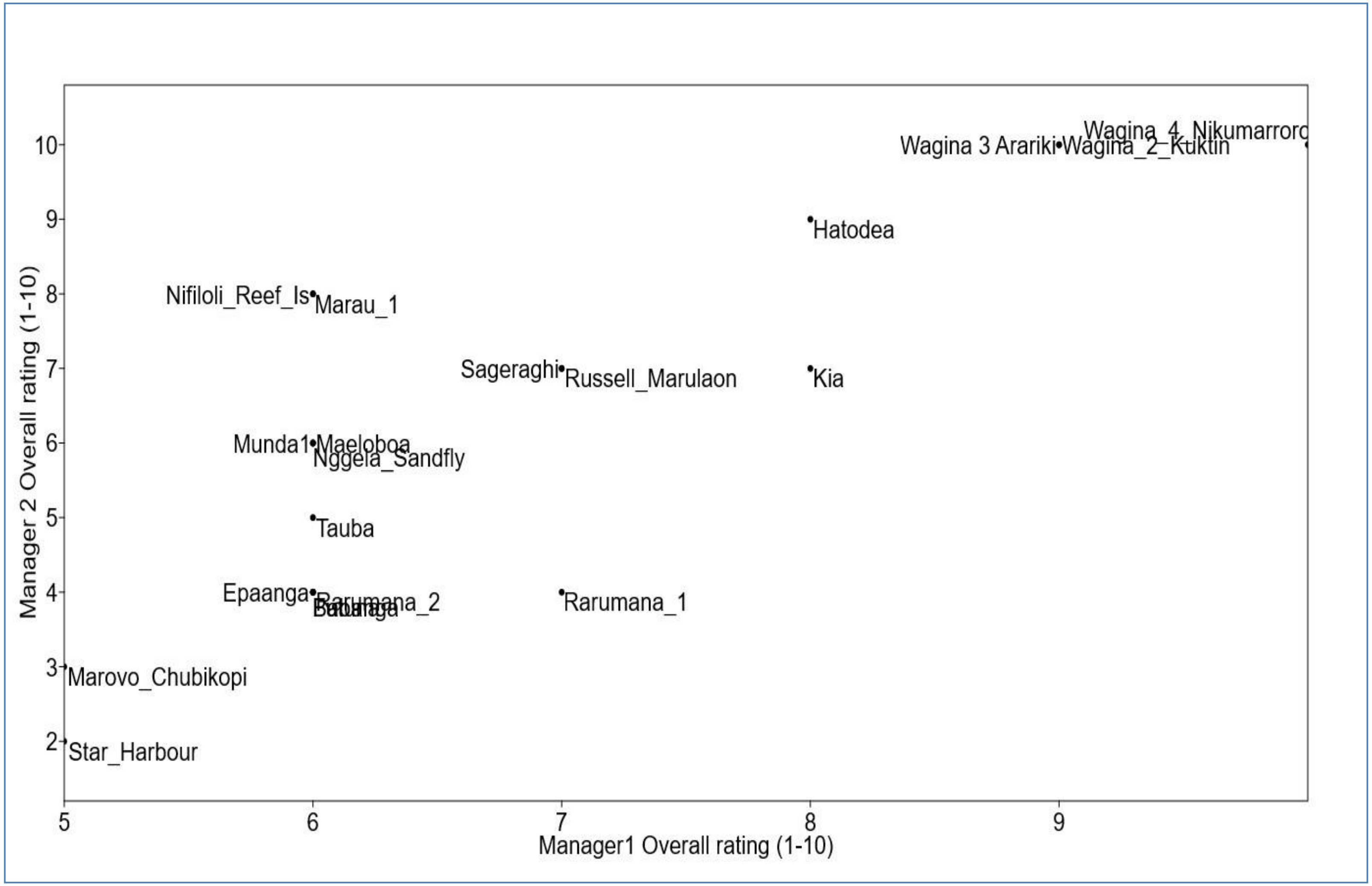

Figure 9. Comparison of overall rating of site suitability for seaweed farming for Manager 1 and Manager 2 (r=0.8, P<0.001).

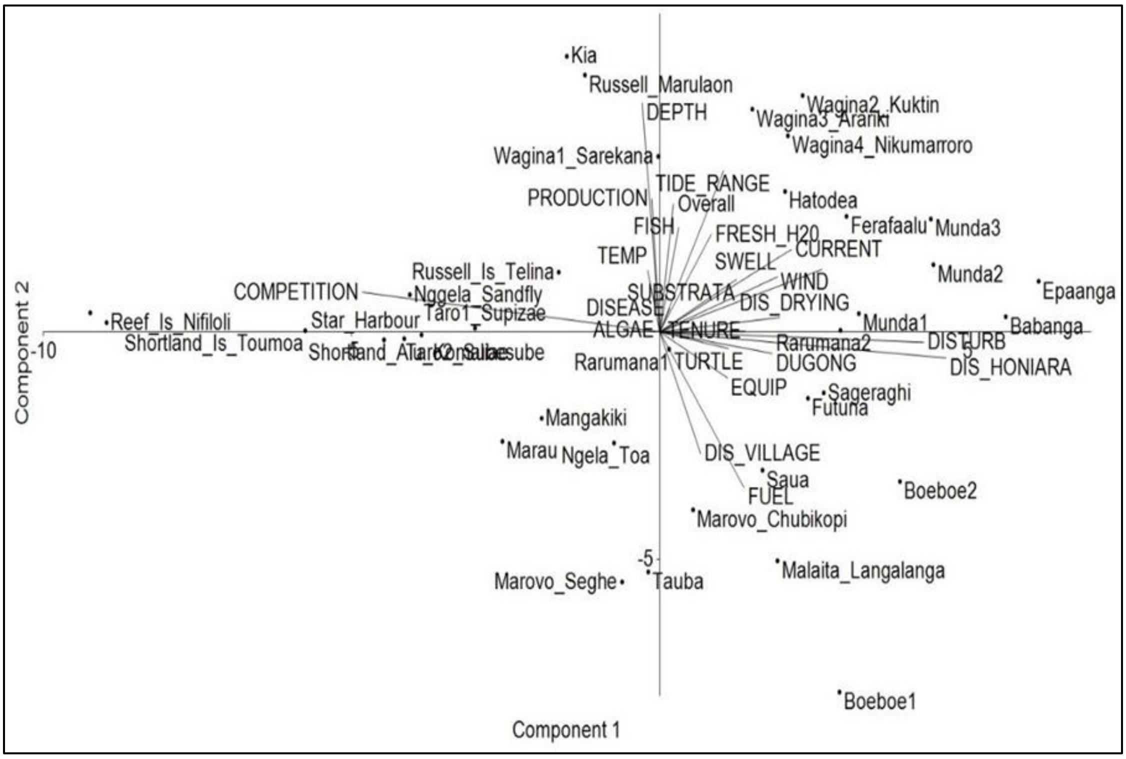

Figure 10. Principal components analysis (PCA) for ratings of seaweed farm suitability by Manager 1. Principal component axes 1 and 2 (29 % and 23 % of variance explained).

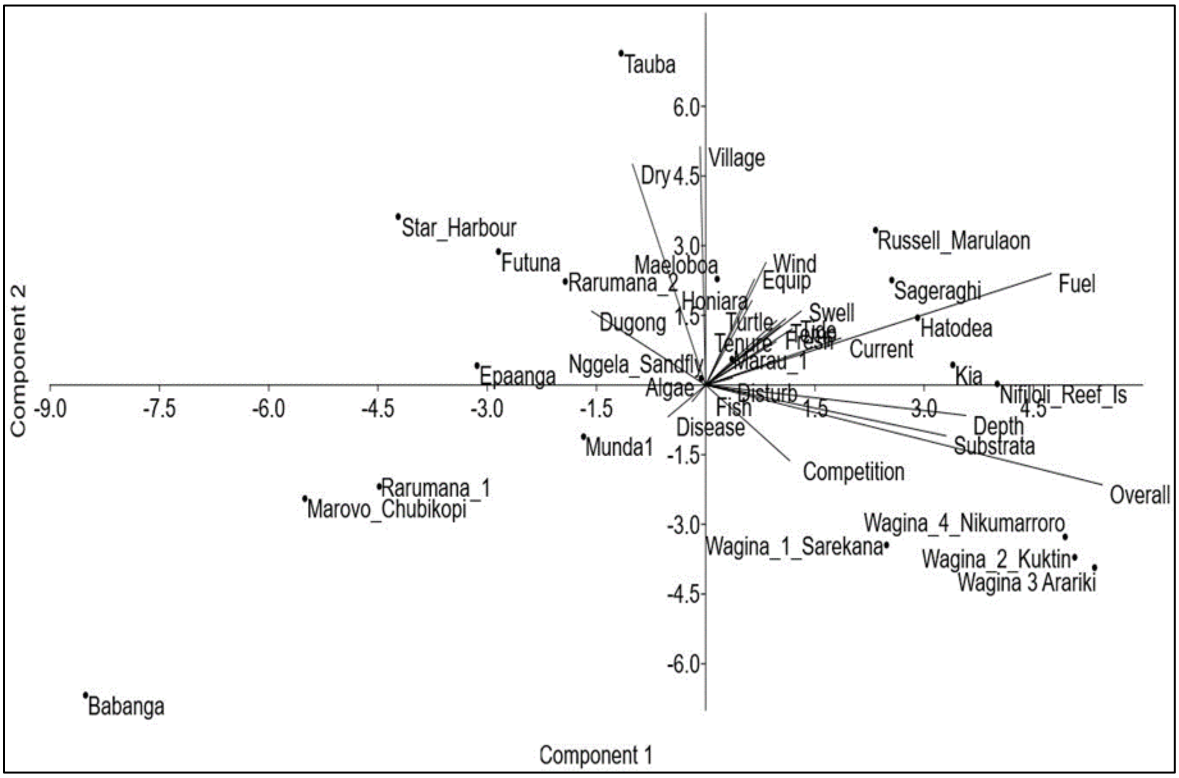

Figure 11. Principal components analysis (PCA) for ratings of seaweed farm suitability by Manager 2. Principal component axes 1 and 2 (32 % and 22 % of variance explained).

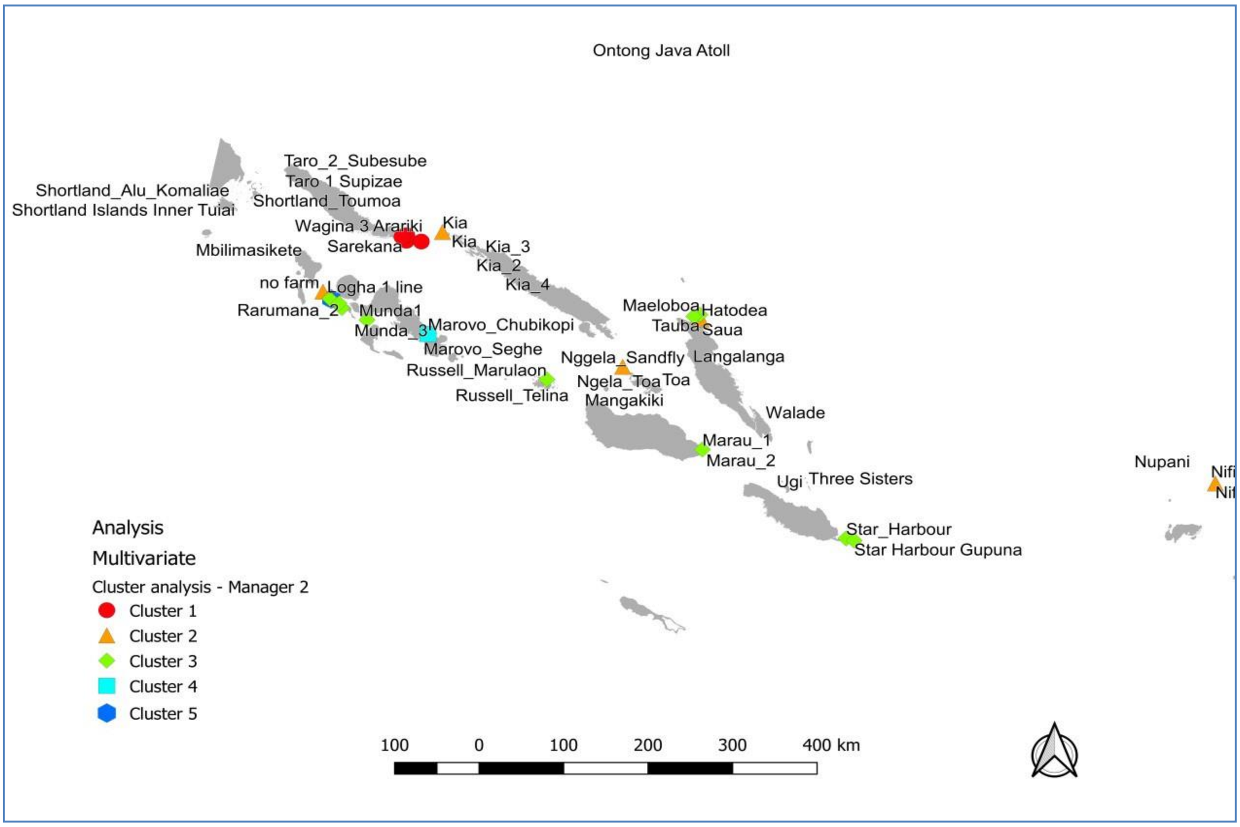

Figure 12. Cluster analysis of site suitability ratings for Manager 1.

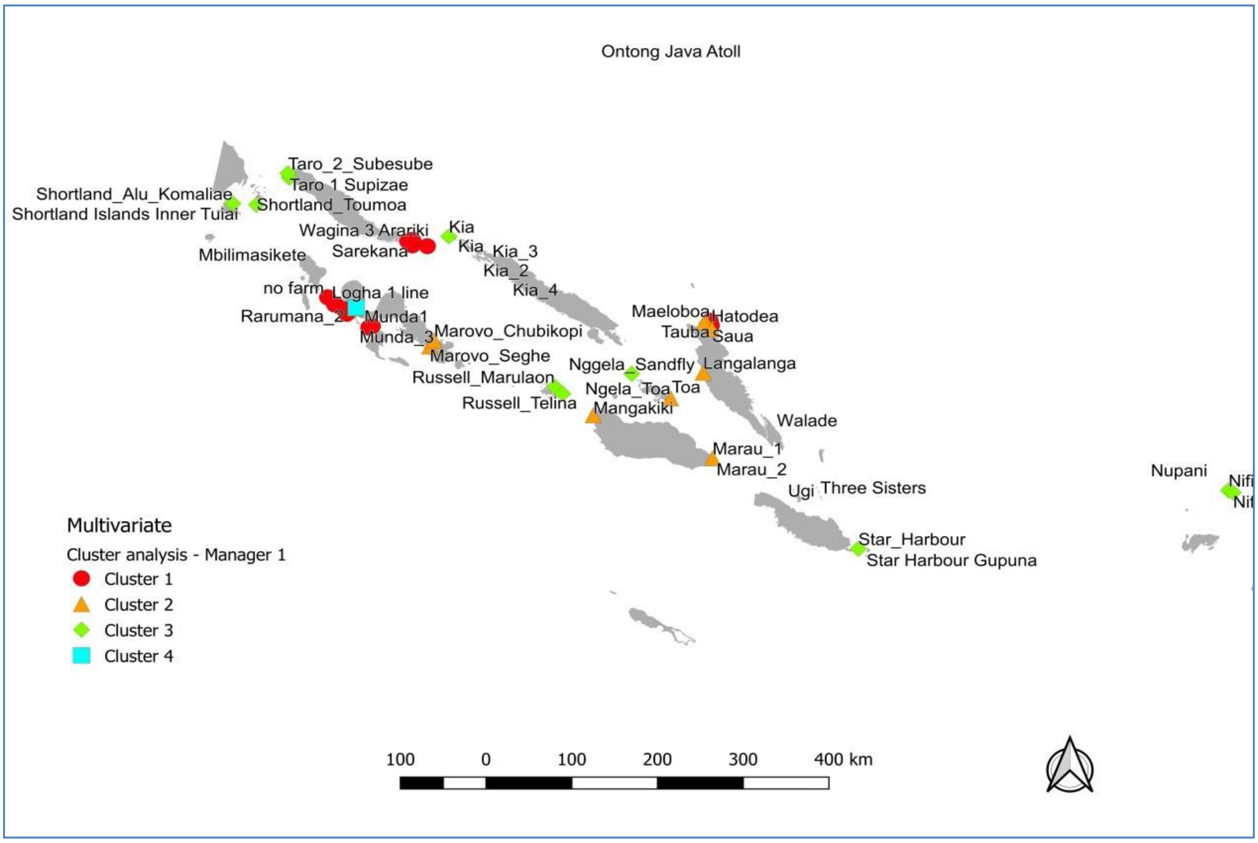

Figure 13. Cluster analysis of site suitability ratings for Manager 2.

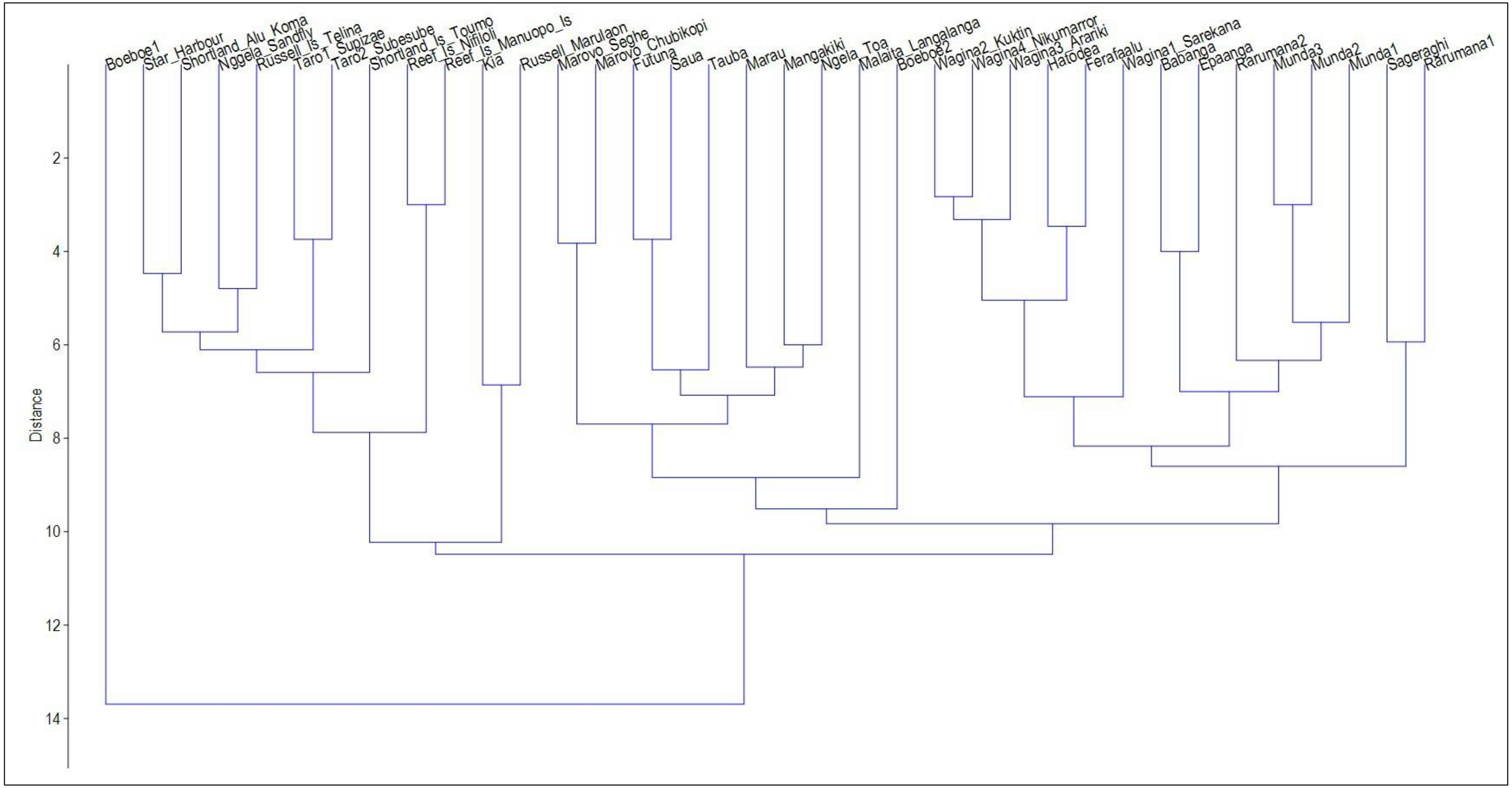

Figure 14. Cluster analysis of Euclidean distances between seaweed farm sites for Manager 1.

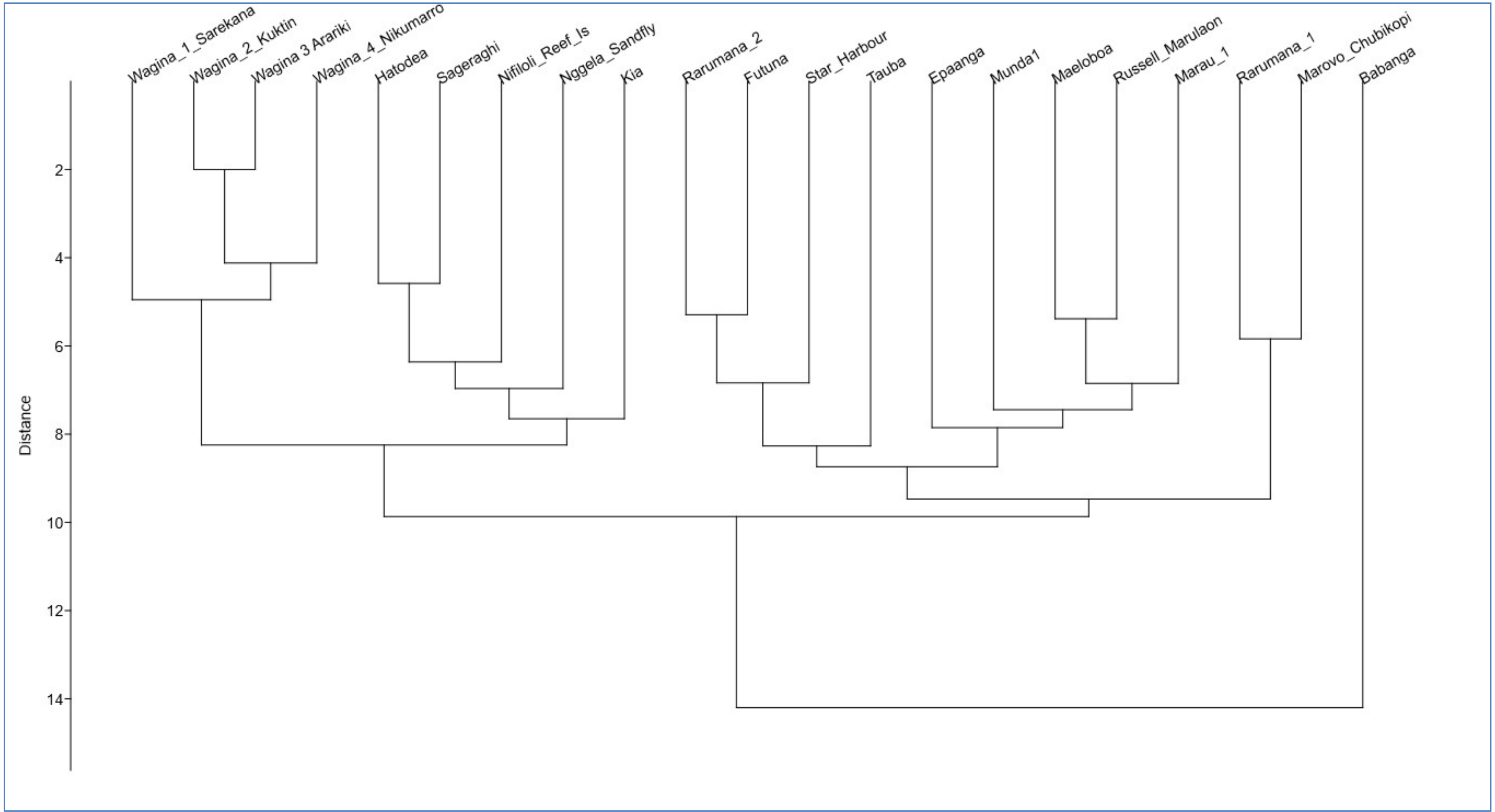

Figure 15. Cluster analysis of Euclidean distances between seaweed farm sites for Manager 2.

3.4 Geospatial analyses

Two approaches were used to estimate and assign measures of proximity for different locations to features such as the nearest mainland, islands, rivers, villages, towns, capital, seagrass beds, mangroves and marine protected areas. In the first, distances were assigned to each IMaRS-USF reef habitat polygon. This allows subsets of habitat polygons to be queried according to combinations of decision rules as used in Vavia (2018). For example, select all the reef habitat polygons over 5 ha in size that are shallow terrace, within 1 km of an island, greater than 2 km from rivers and within 200 km of Honiara.

For display at a national scale and displaying measures for specific potential farm sites, the mean values of all polygons were assigned to a central point for each farm and the distances of the points themselves from environmental and socio-economic features also calculated. In most cases, the latter distances were sufficient for most regional and national overviews, as shown in Figure 16 which shows a mostly longitudinal trend in distances from the country's capital, Honiara.

A PCA of potential farm sites described by geographic proximity to 20 features (e.g. mainland, island, river, road, wharf, shipping route, town, seagrass bed, protected area) in Figure 17 is dominated by the area of 'shallow terrace with constructions' at the Reef Islands and the distances to features found only on larger more central islands. In the top right-hand quadrant, Kia, Wagina 4 and the Shortland Islands stand out for their relatively large distances to villages, shipping routes, and wharves, but relatively large area of shallow terrace habitat.

Figure 18 shows approximately three to four clusters of similar sites based on the proximity data with the Reef Islands (Nifioli) standing out from all other sites; Wagina, Kia and most Western Province sites in a large group; the Shortlands, Taro and Marovo splitting off; and Marau, Sandfly, Ngela, Langalanga, Hatodea and other sites forming another large group.

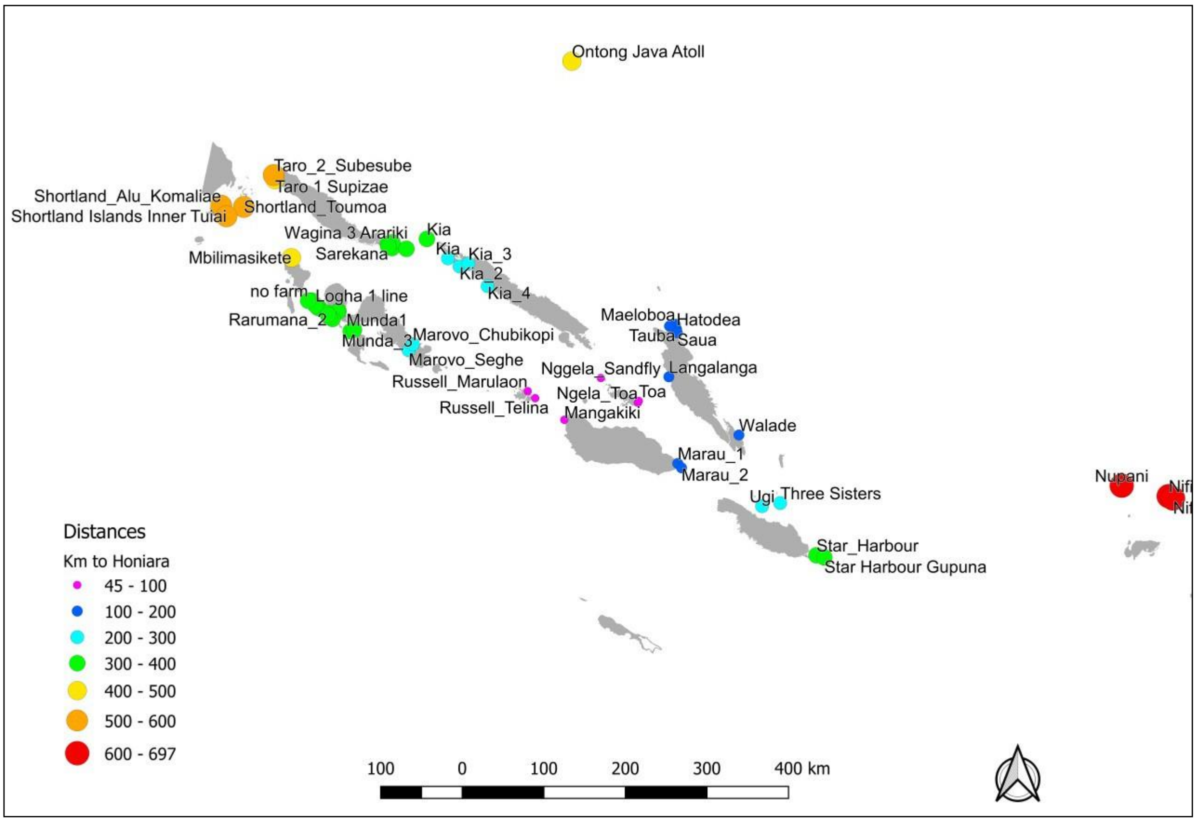

Figure 16. Example of geospatial proximity analysis – distance of sites (km) to Honiara.

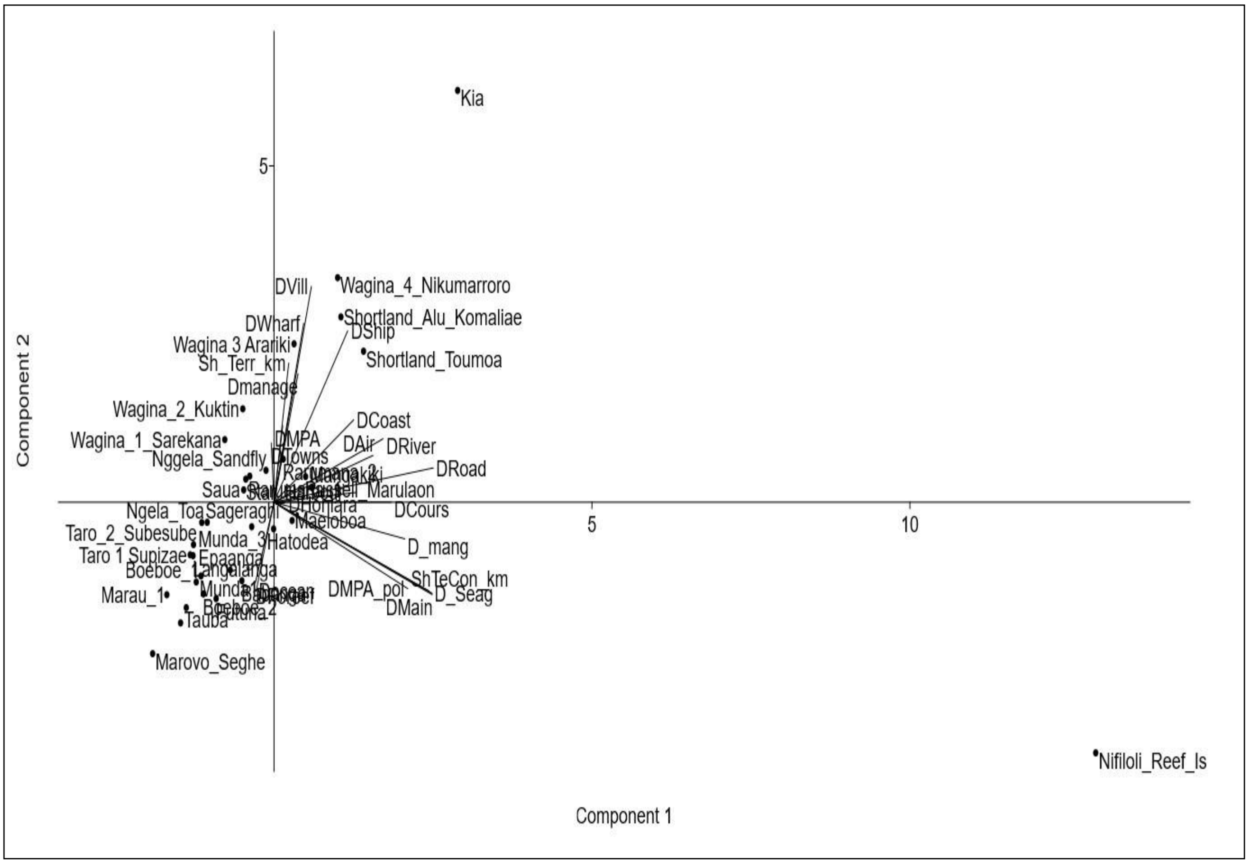

Figure 17. Principal components analysis (PCA) for GIS point estimates of seaweed farm suitability. Principal component axes 1 and 2 (33 % and 16 % of variance explained).

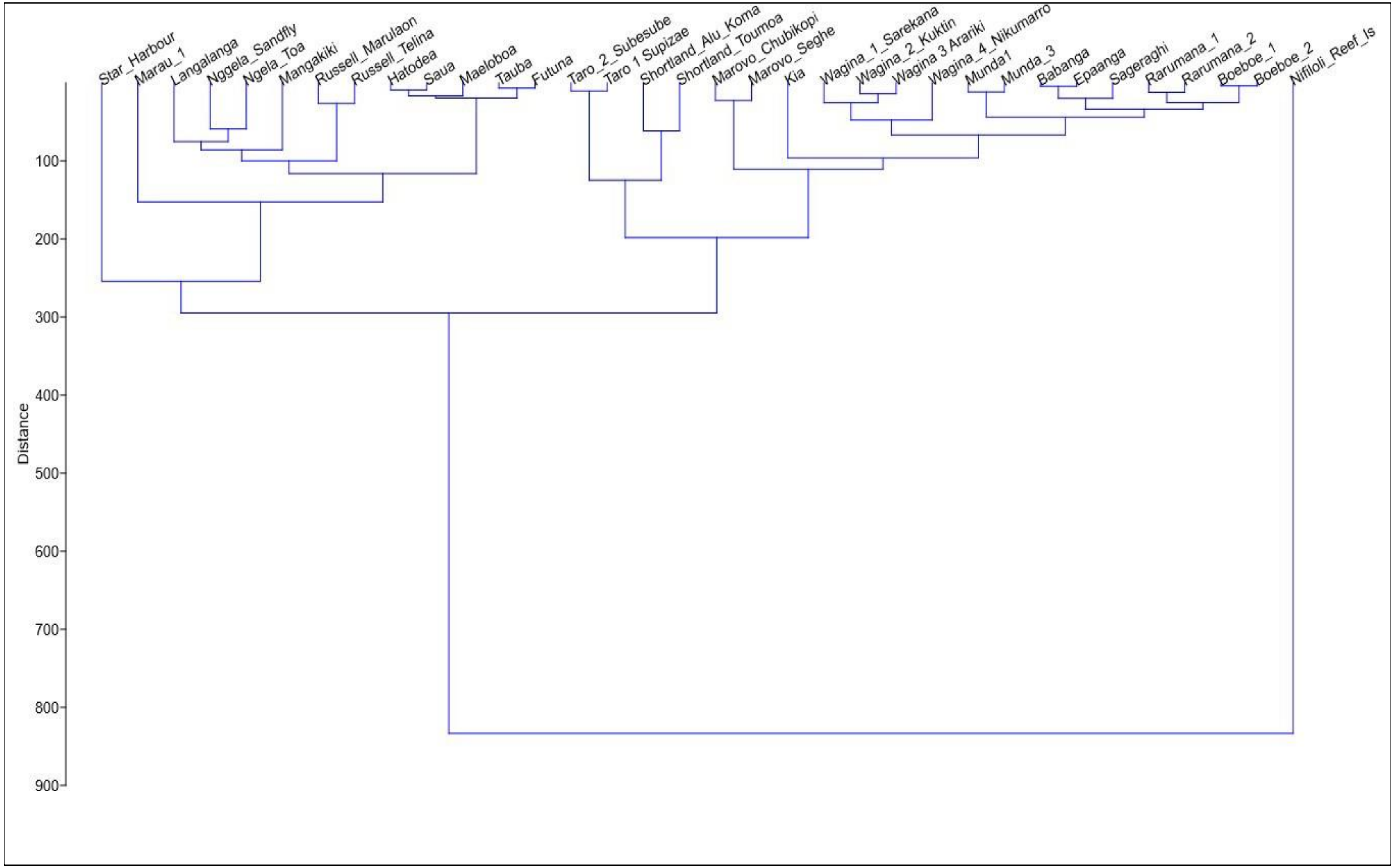

Figure 18. Cluster analysis of seaweed farm-site similarity based on geospatial variables.

3.5 Multiple criteria analysis

The Criterion Decision Plus software allows users to interactively query data for variables and alternatives (potential farm sites in this case), explore how different priorities and weightings effect outcomes and use sensitivity analysis and trade-offs to explore options. Each model holds information from many different sources, formats and scales in a central standardised environment that can be easily manipulated.

The input variables from the expert ratings and geospatial analysis and the resulting multiple criteria scores are shown in Figures 19 to 30. Although displayed in separate figures, the four data source categories (Manager 1, Manager 2, GIS point data, GIS polygon data) are part of the same model. At each level of the hierarchy, sub-criteria can be weighted, examined separately or excluded from the analysis.

Weighted multiple criteria scores for expert ratings and criteria weights from Manager 1 and Manager 2 are mapped in Figures 19 to 24. For Manager 1, there are similar groupings of higher suitability sites at Wagina, Kia and Western Province and lower scores for the smaller, more central islands and outlying locations in the Shortland and Reef Islands (Figures 19 and 22). For Manager 2 (Figure 20 and 24) there are also medium to high scores for Wagina, Kia and the Western Province but higher scores for Marau, Maeloboa, Marulaon and the Reef Islands (Nifioli).

While there are some scatter and several influential outliers, there is a weak positive correlation (Figures 23 and 24) between the overall suitability ratings from Manager 1 ($r=0.28$, $P>0.1$) and Manager 2 ($r=0.4$, $P=0.07$) and their weighted multiple criteria scores. This is not surprising given that the data sources are similar, but it does indicate some consistency in subjective scoring and weighting.

The geospatial point (Figure 28) and polygon (Figure 30) unweighted scores show quite different overall site scores for suitability and do not correlate well with the managers' ratings (Figures 31 and 32). However, these criteria have not been weighted according to importance of their effect on suitability. The available geospatial data also differed markedly to the expert judgement scores both in the kinds of variables addressed and in the types of suitability measures used to score sites.

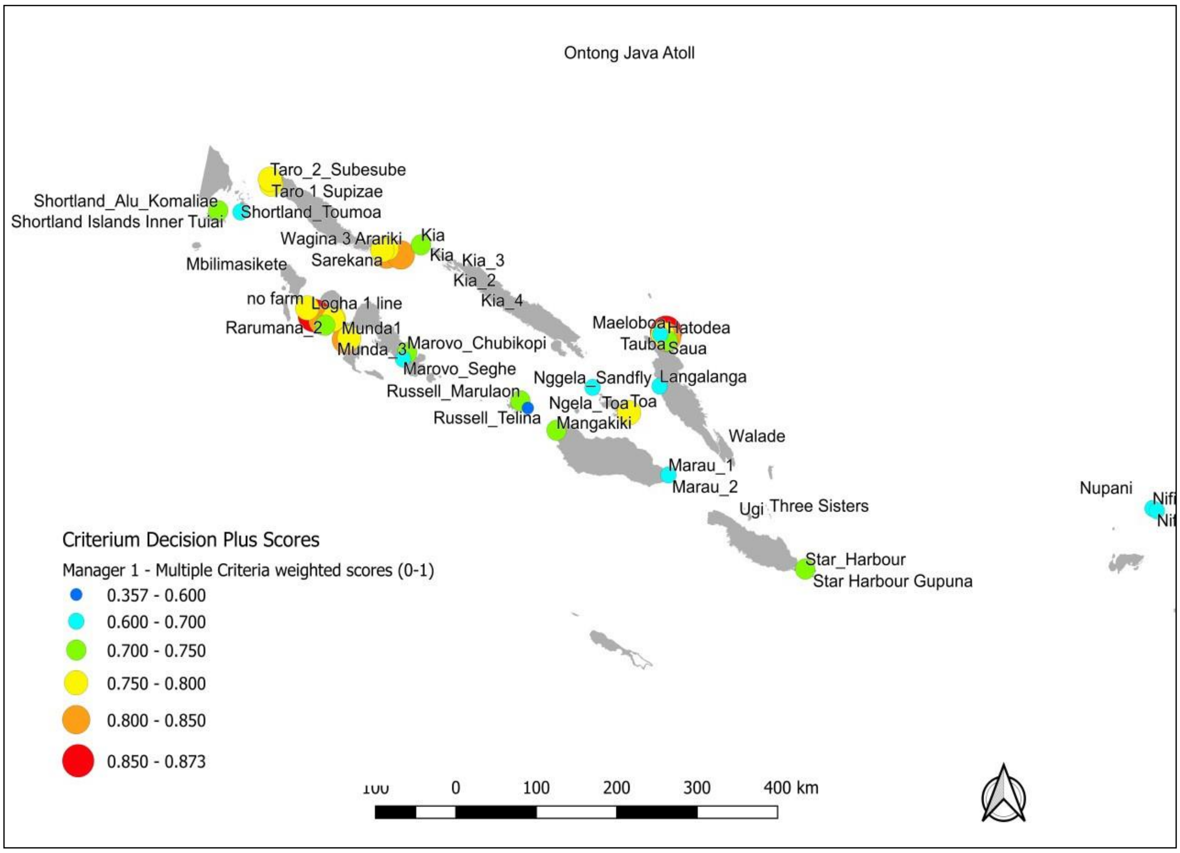

Figure 19. Combined weighted multiple criteria score of site suitability for criteria from Manager 1.

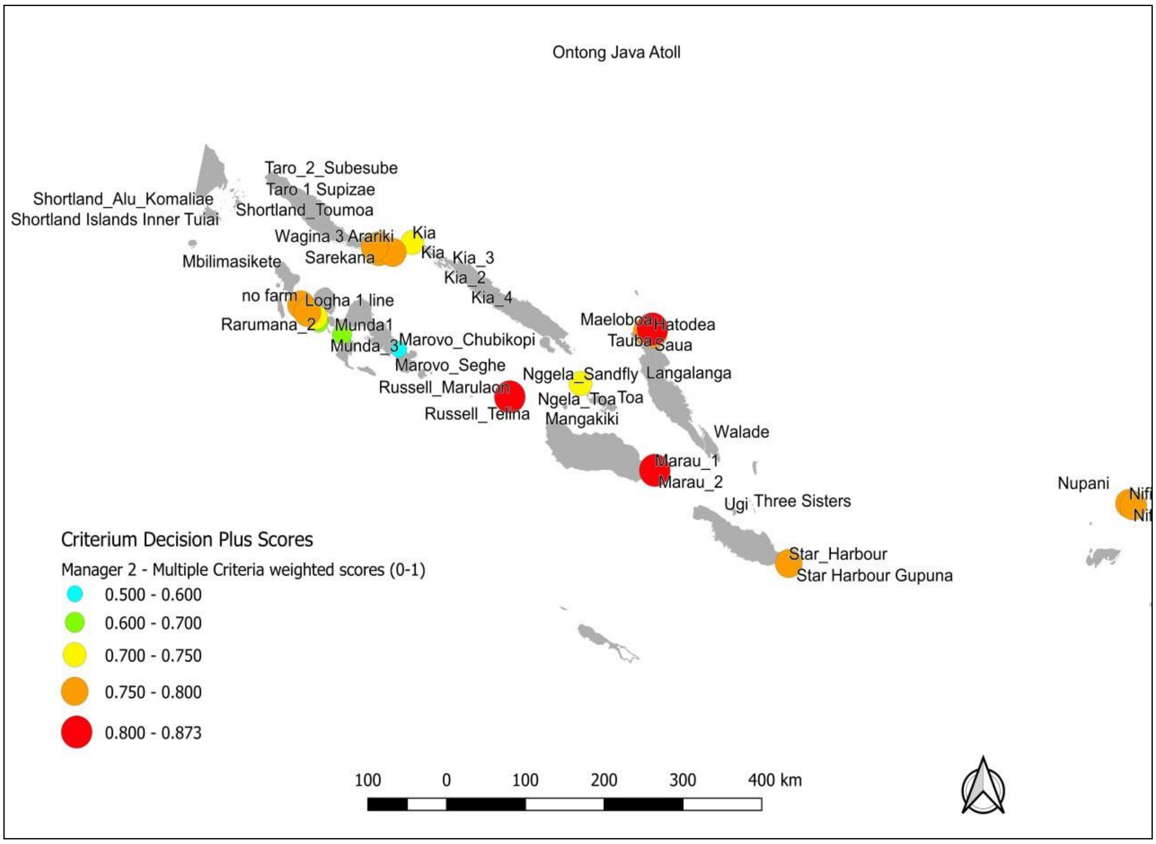

Figure 20. Weighted multiple criteria score of site suitability from Manager 2.

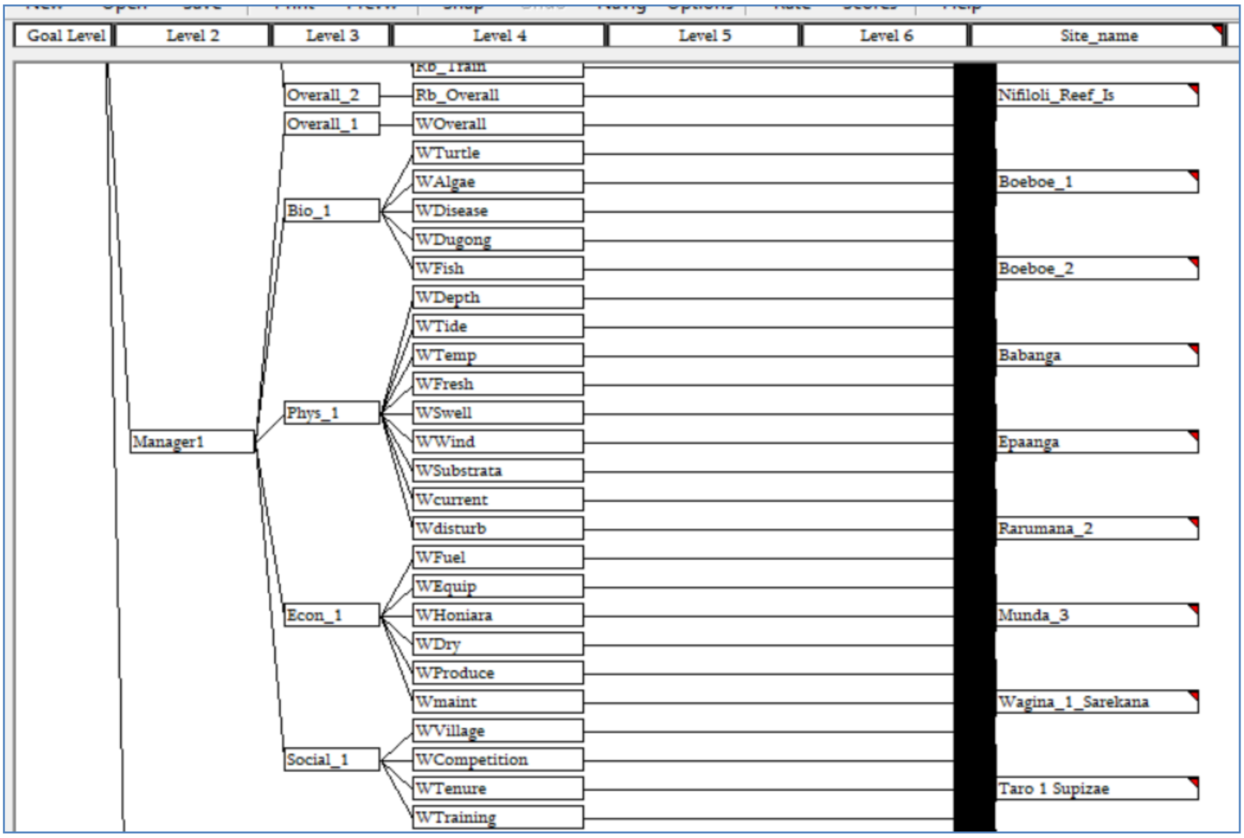

Figure 21. Section of a Criterion Decision Plus multiple criteria model for just Manager 1 ratings nested within biological, physical, economic and social sub-criteria.

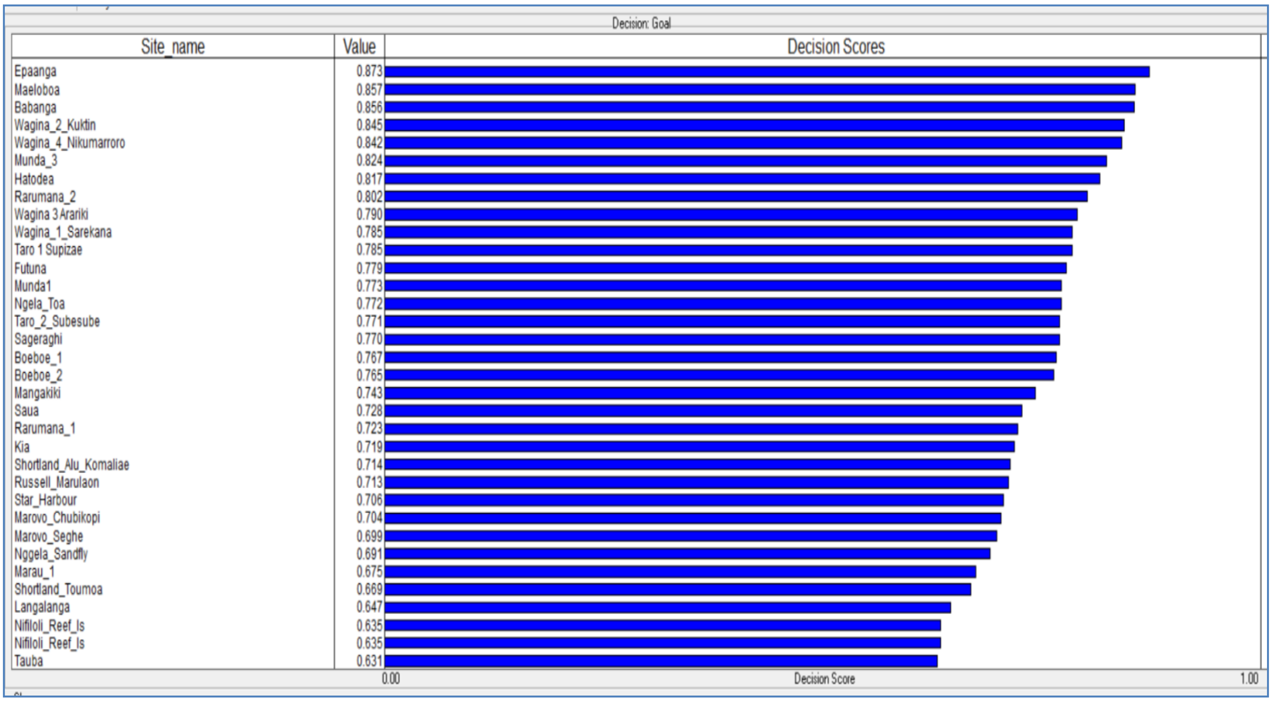

Figure 22. Combined multiple criteria scores of the overall suitability of potential seaweed farm sites for just Manager 1 (other data sources excluded). All criteria are weighted by the level of importance assigned to each criterion by the manager.

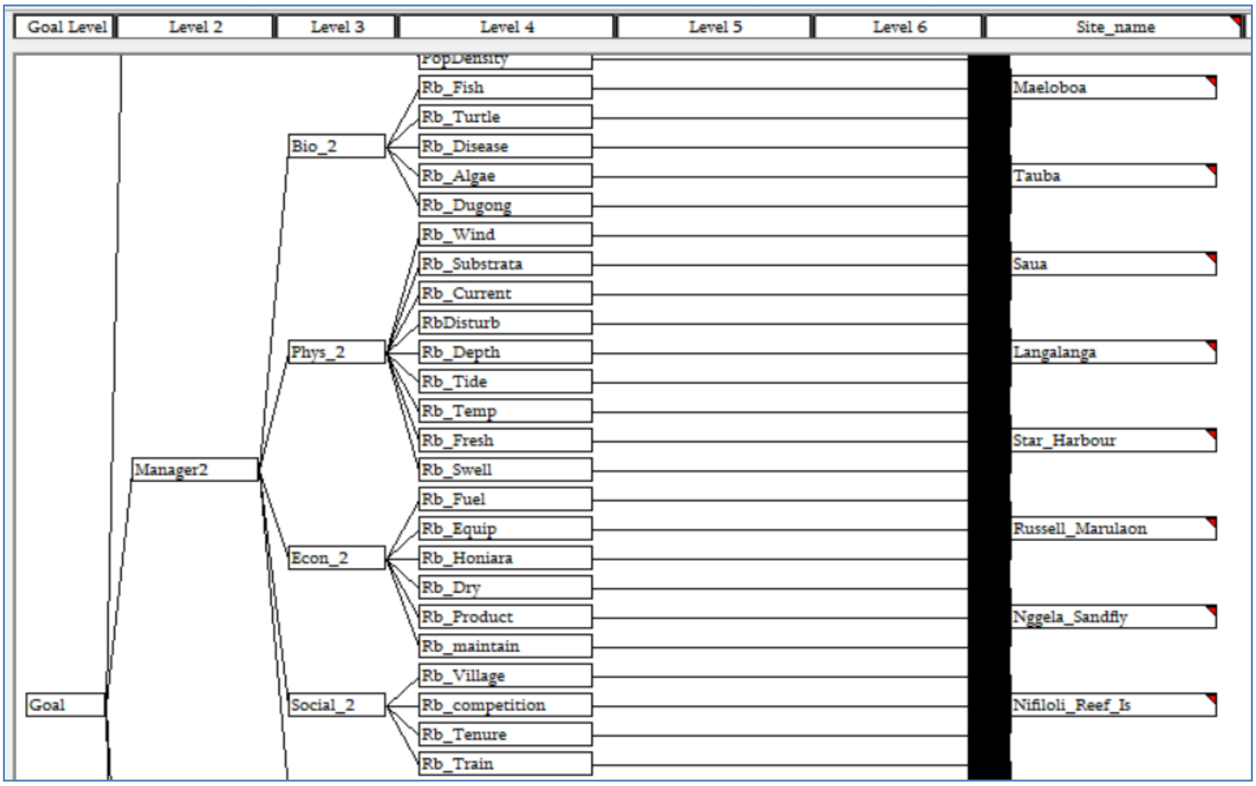

Figure 23. Section of a Criterion Decision Plus multiple criteria model for just Manager 2 ratings nested within biological, physical, economic and social sub-criteria.

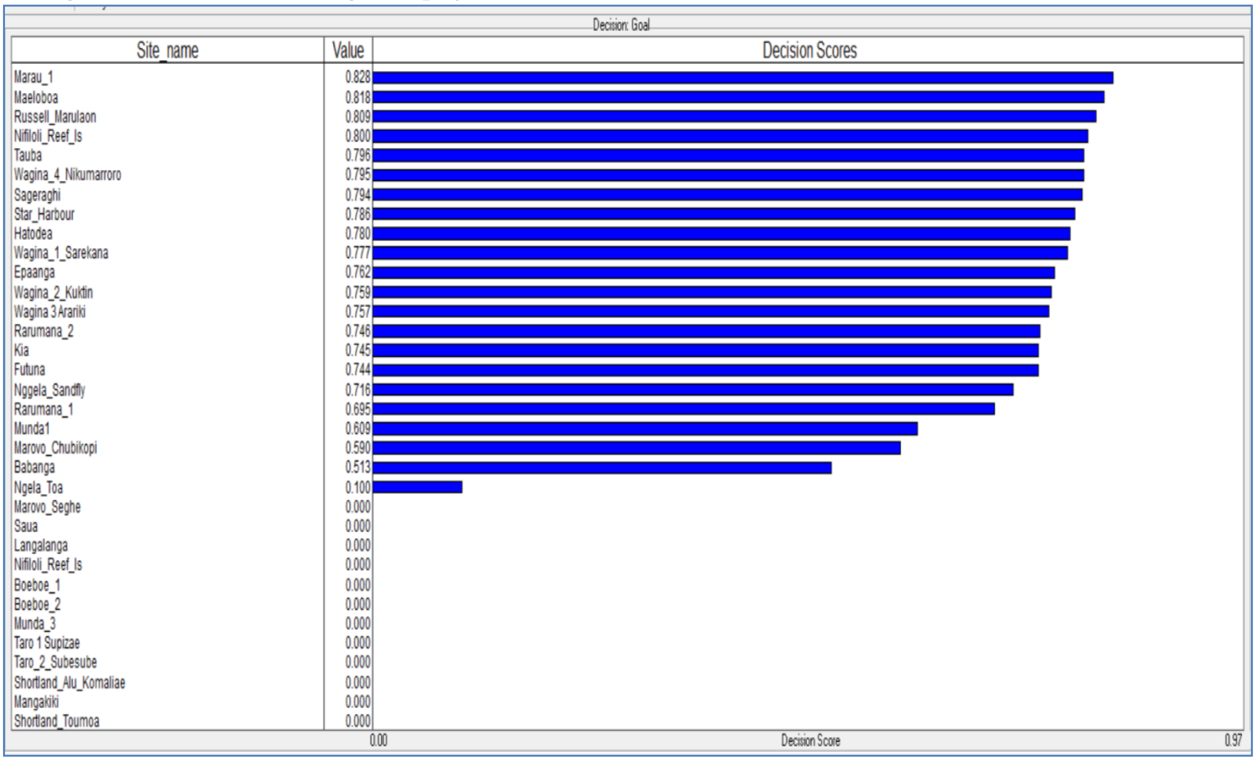

Figure 24. Combined multiple criteria scores of the overall suitability of potential seaweed farm sites for just Manager 2 (other data sources excluded). All criteria are weighted by the level of importance assigned to each criterion by the manager.

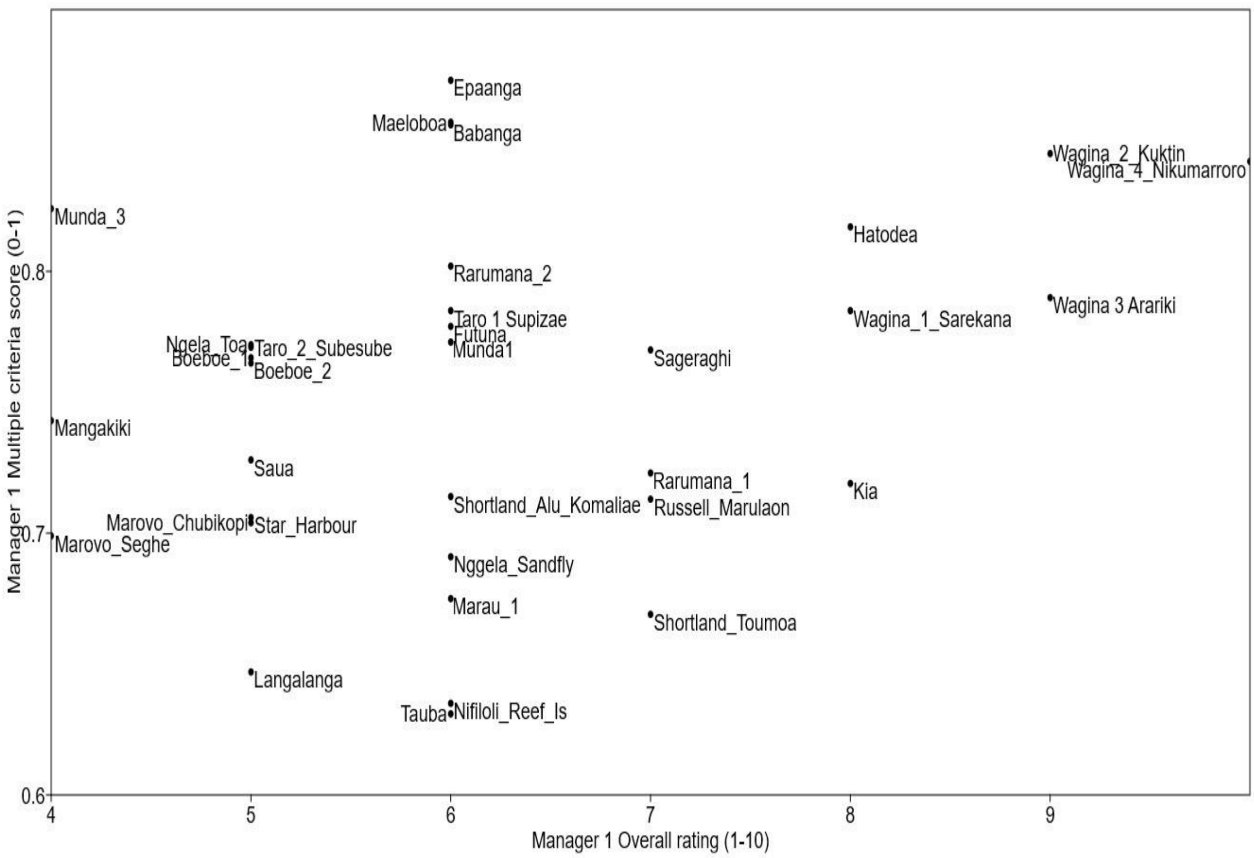

Figure 25. Comparison of overall rating of site suitability for seaweed farming for Manager 1 with weighted multiple criteria scores for Manager 1 (r=0.28, P>0.1).

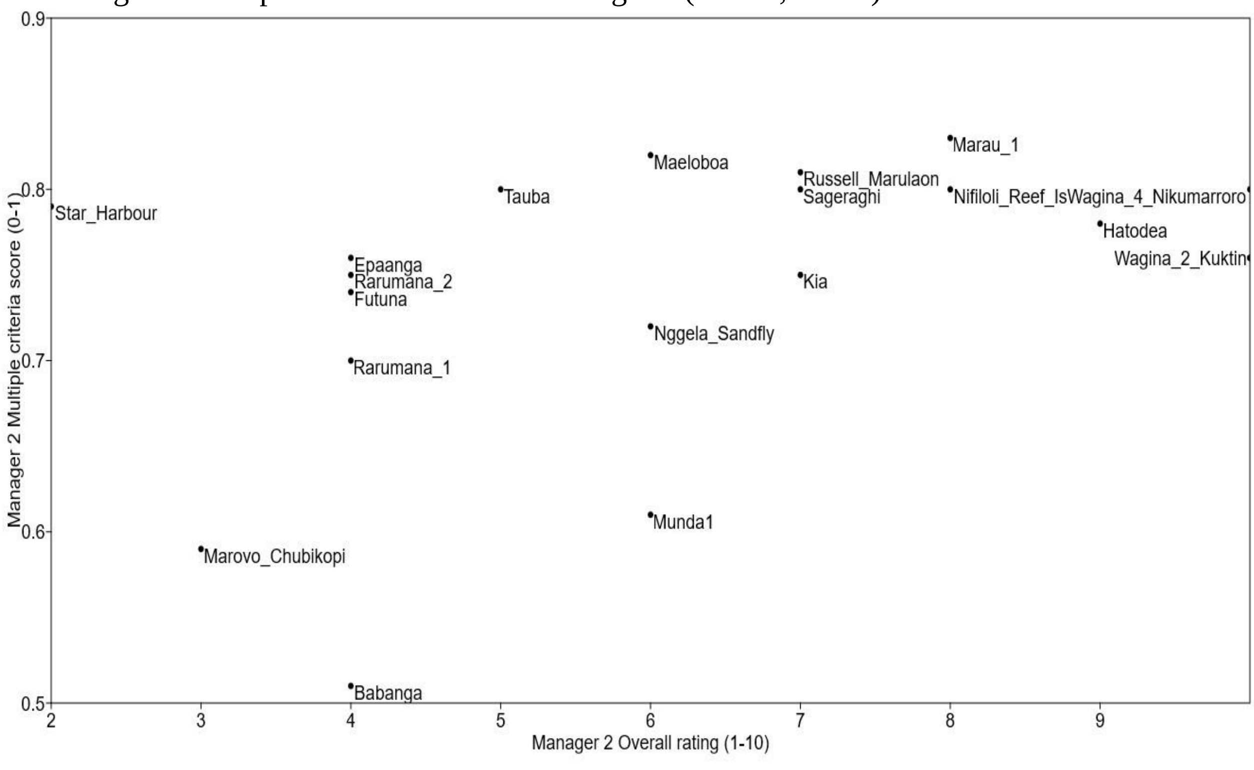

Figure 26. Comparison of overall ratings of site suitability for seaweed farming from Manager 2 with their weighted multiple criteria scores (r=0.4, P=0.07).

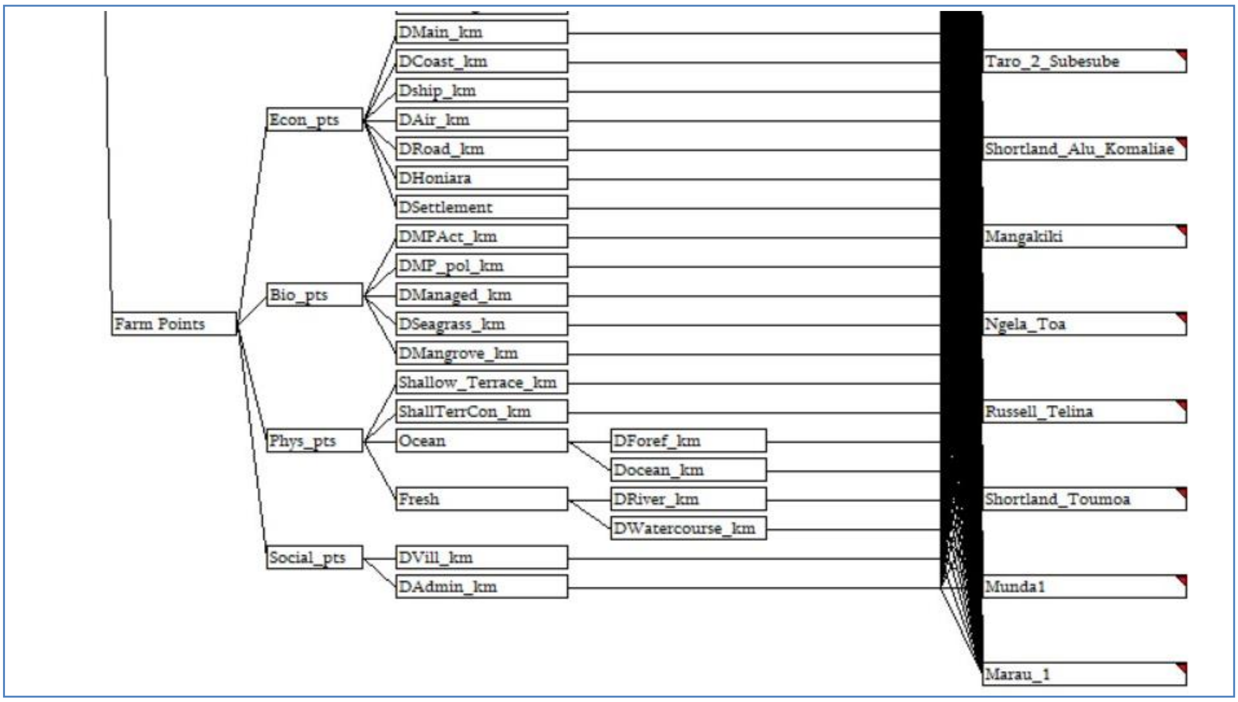

Figure 27. Section of a Criterion Decision Plus multiple criteria model for GIS point distances and areas nested within biological, physical, economic and social sub-criteria.

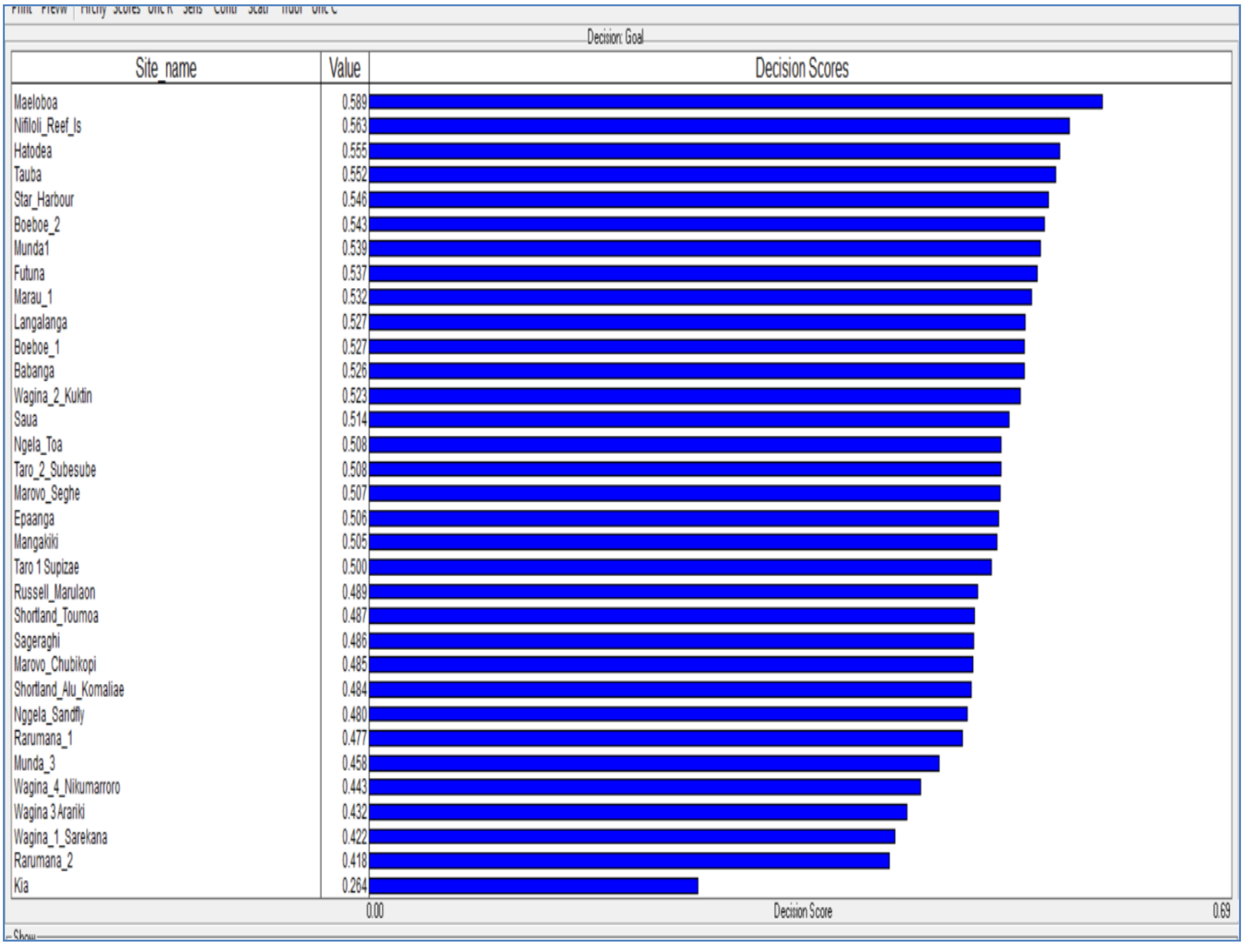

Figure 28. Combined multiple criteria site scores of suitability for seaweed growing derived from GIS point distances and areas (other data sources excluded). A spatial representation of these scores can be viewed in the QGIS project application.

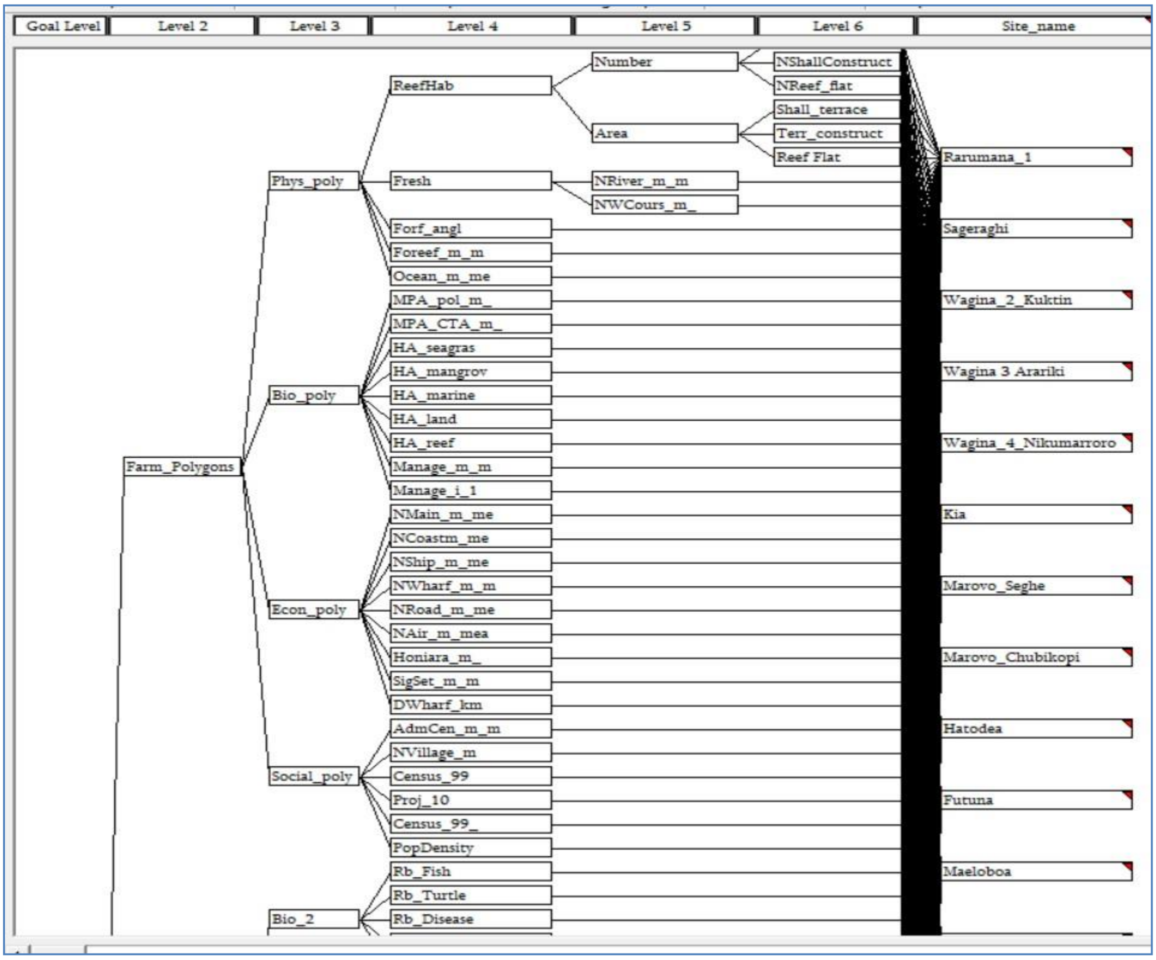

Figure 29. Section of a Criterion Decision Plus multiple criteria model for mean GIS polygon distances and areas nested within biological, physical, economic and social sub-criteria. This part of the model is not weighted but this can be done interactively within the software.

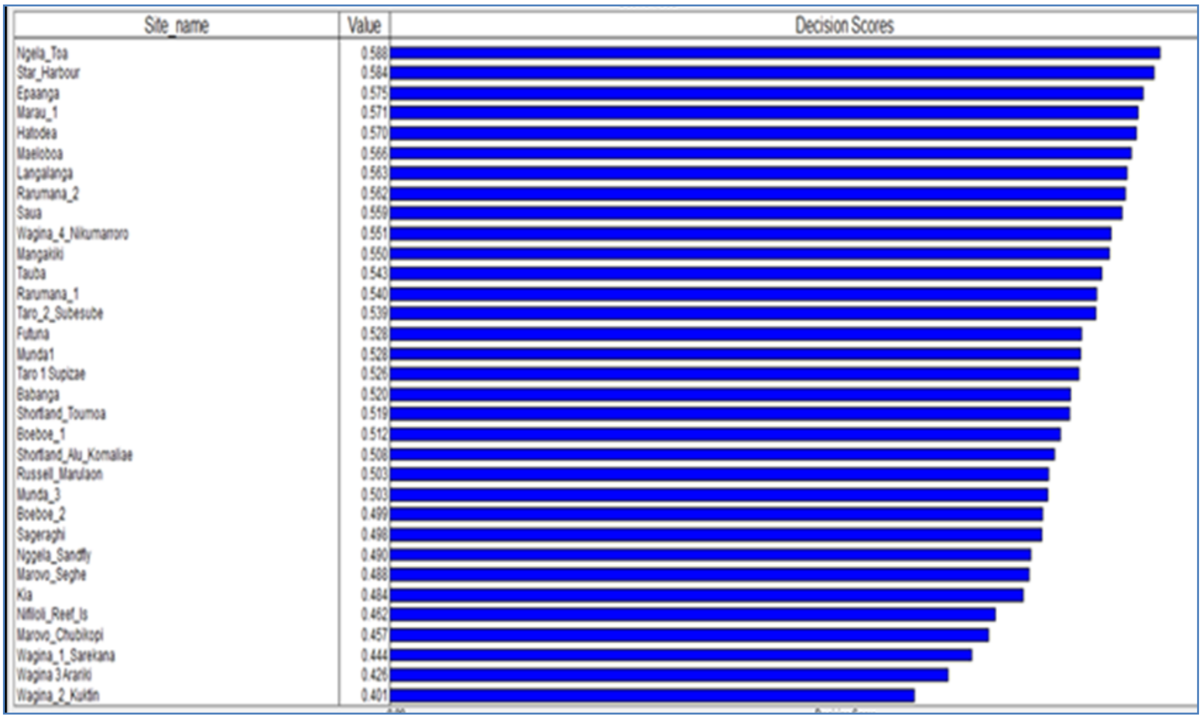

Figure 30. Combined multiple criteria scores of suitability for seaweed growing derived from mean GIS polygon distances and areas.

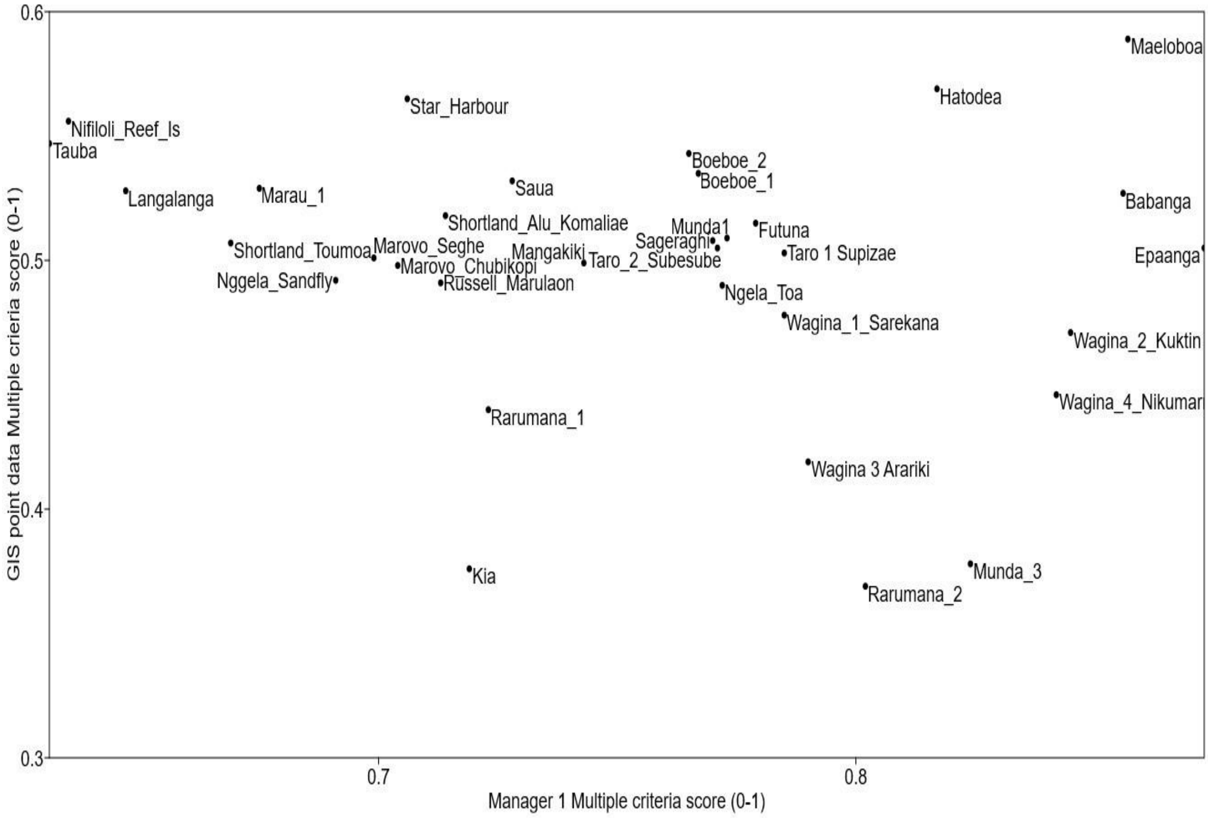

Figure 31. Comparison of the multiple criteria scores for Manager 1 with unweighted multiple criteria scores for the GIS point data (r=-0.2, P>0.1).

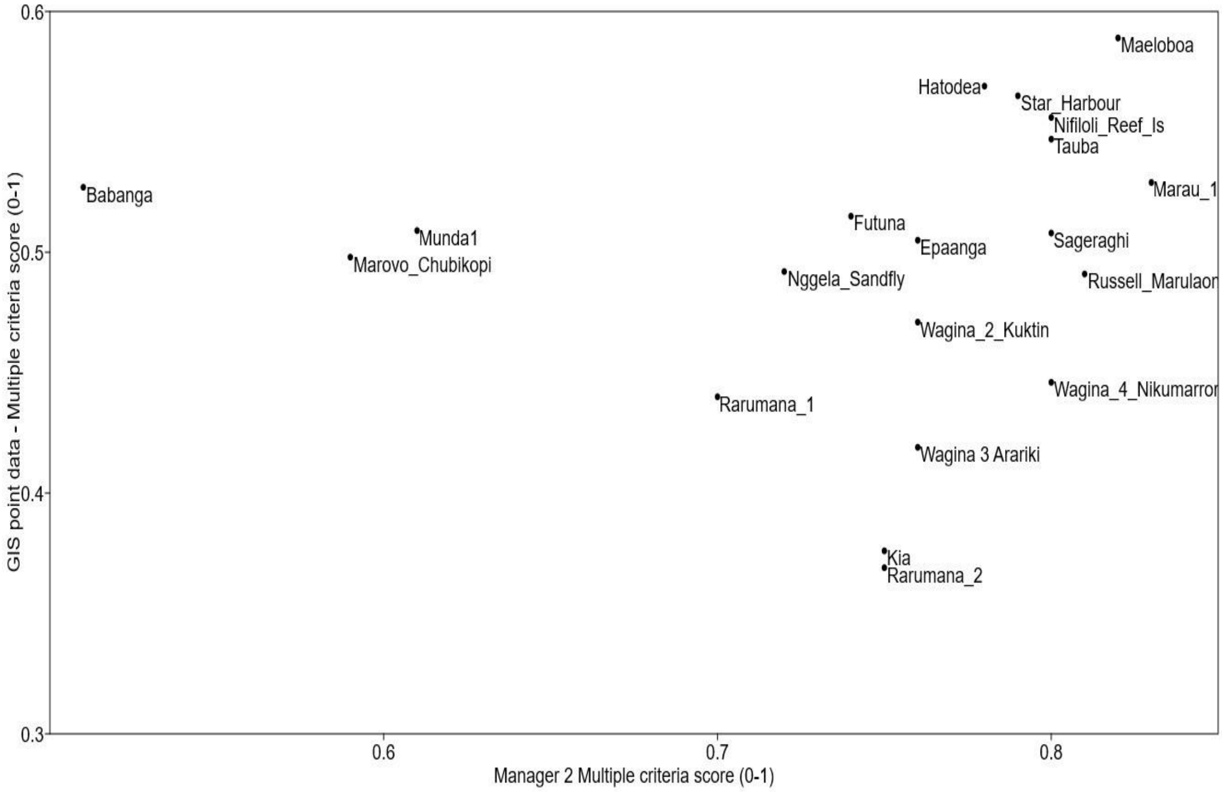

Figure 32. Comparison of the multiple criteria scores from Manager 2 with the unweighted multiple criteria scores for GIS point data (r=0.1, P>0.1).

3.6 Interpretation of satellite, drone imagery and site inspections

Worldview-2 satellite imagery from the ESRI base maps in ArcGIS and other web services provided variable but high resolution images of seaweed farms. These were sufficiently detailed to hand-digitise and georeference boundaries of farms near Wagina Island on two dates (Figures 33 and 34). It was, however, difficult to determine the age of the farms and which, for example, were currently farmed. Images were also often affected by cloud and their availability was restricted by time and by cost. However, they could feasibly be used to map changes in the extent of farms.

Aerial photographs captured by drone provided high resolution, georeferenced, photo-mosaics at five locations in the Western Province (Figures 35 to 39). The drone was able to cover a few hectares and complete a detailed photo survey in a short 15 minute flight and the scope of the survey could easily be increased with higher altitudes and flying speeds.

Substrata, corals, seagrass, algae, depth zones and existing and previous seaweed farms could be more easily interpreted from the drone images when compared to the satellite imagery, but for a smaller area. Both sources of imagery were useful in interpreting the IMaRS-USF marine habitat classification and the boundaries of potential sites. The resolution of the mosaics is sufficiently high to detect relatively short-term changes in coastal habitat as evident in the study by Chan (2018) on land use at a coastal village (Figure 45). It was evident that drone imagery could provide useful site information for farm development, planning, permitting and monitoring.

The imagery is especially suitable for finer scale mapping and quantifying areas within sites perhaps identified from coarser scale data. The resolution makes it possible to distinguish between slight but important differences in depth and substrata such as small boulders and stones (Figure 35), seagrass and, in some areas, sediments oriented along dominant currents. Drone photogrammetry has other applications including 3D modelling, mapping of important ecological areas like seagrass, coral, and mangroves, change detection of human development including seaweed farms. Training and equipment to conduct ongoing drone surveys was therefore provided to the Ministry of Fisheries and Marine Resources staff.

The seabed at seven sites (Vona Vona, Boe Boe1, Boe Boe2, Babanga, Epaanga, Logha and Sageraghi) were surveyed on snorkel to help interpret relationships between satellite data, GIS habitat maps, aerial photo interpretation and the benthic substrata and epibenthos. These sites were also surveyed by drone with the exception of Boe Boe 1 and Epaanga.

Babanga and Epaanga lie sheltered behind islands on the leeward side of reefs. As at Logha, there were scattered corals and stony outcrops on patches of sand at these sites (Figures 38 and 39). At Rarumana (Figure 35) and Sageraghi (Figure 36) there was less coral and more large sandy areas and at Sageraghi there were patches of seagrass, *Halimeda* and filamentous algae (Figures 40 and 41).

The snorkel survey was able to confirm the location of the remains of the previous farm at Sageraghi, visible on the drone photo-mosaic (Figure 42). The trial floating longline farms at Boe Boe (Figure 37) were further inshore on the edge of narrow channels and passes in an almost estuarine inner network of small islands. The seabed was mostly fine sand with patches of algae and seagrass. The trial seaweed farms there may have been affected by the slower rates of water exchange. With some small exceptions, the abundance (<5-10 % cover) and diversity of corals and other invertebrates at all sites surveyed was low but patches of seagrass and algae occurred in several areas.

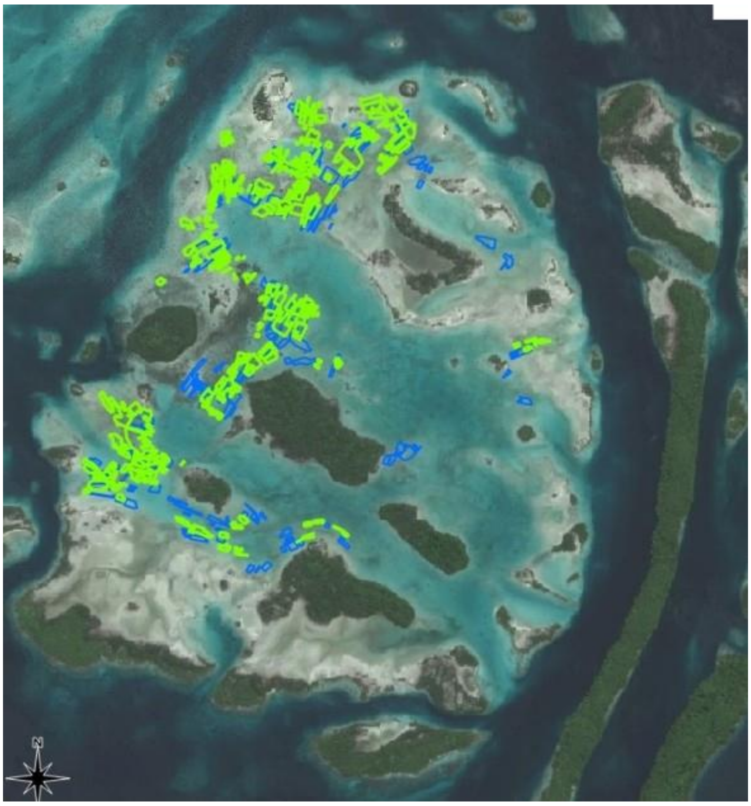

Figure 33. Boundaries of seaweed farms west of Wagina Island digitised from WorldView-2 imagery from November 2013 (green) and October 2015 (blue).

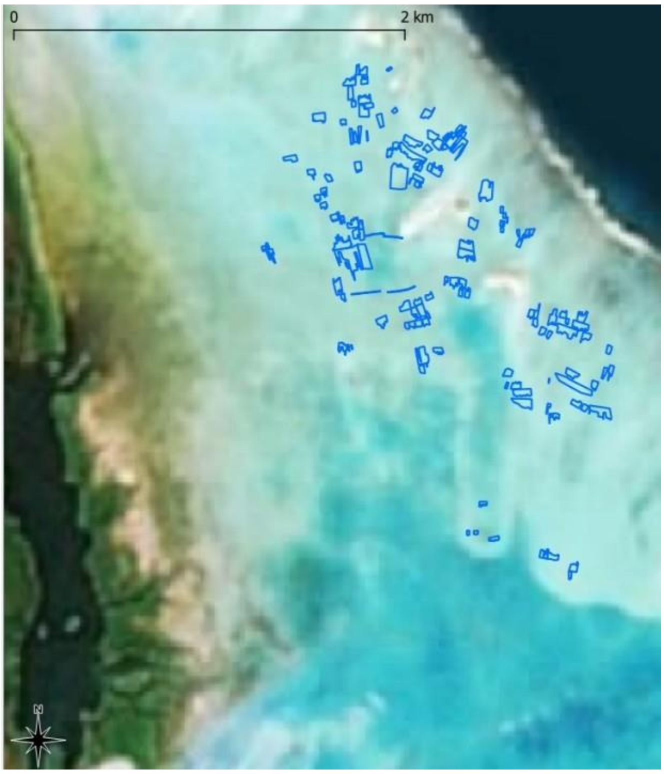

Figure 34. Boundaries of seaweed farms east of Wagina Island digitised from WorldView-2 imagery from October 2015 (blue).

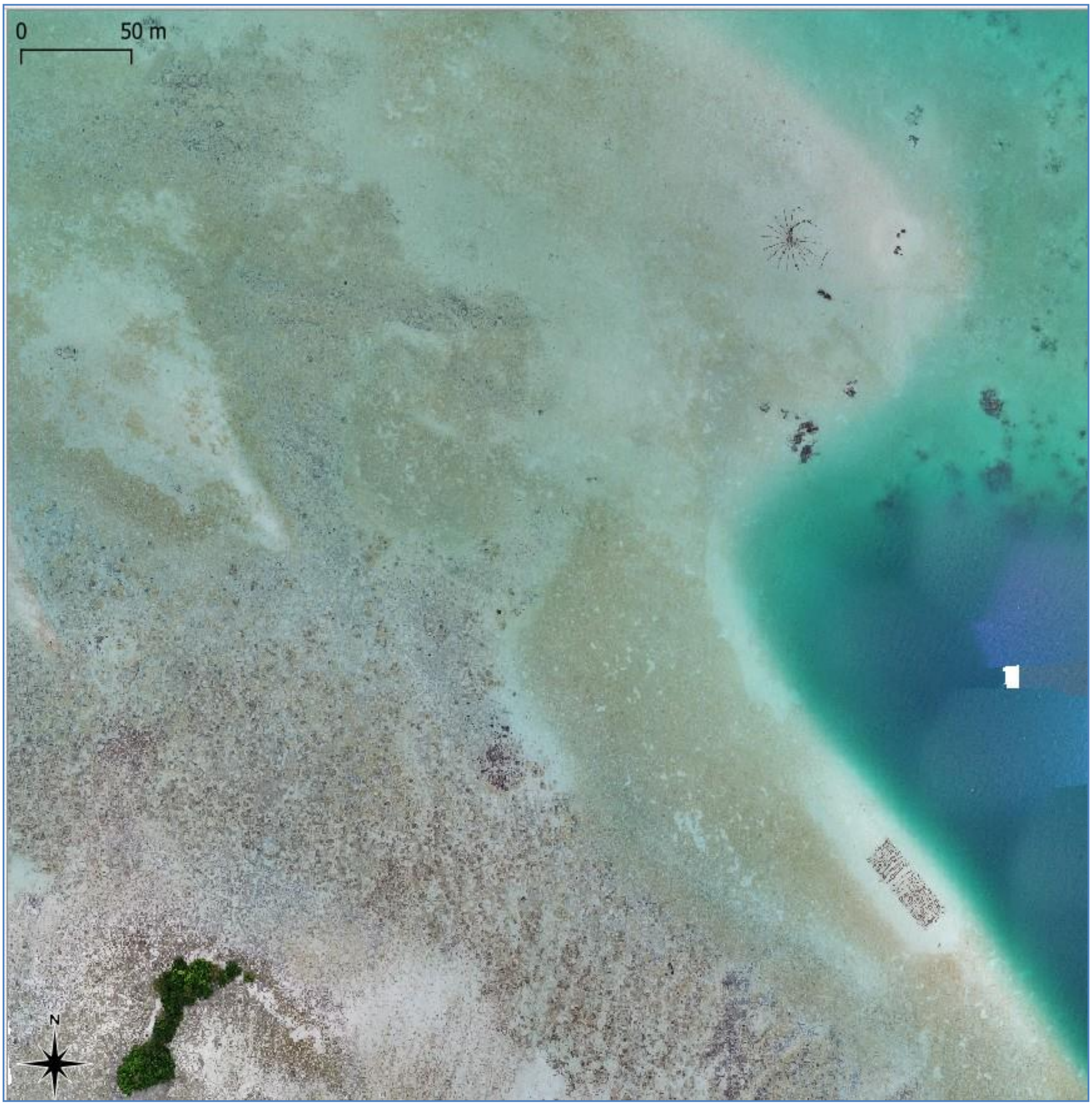

Figure 35. Georeferenced photo-mosaic of reef flat (left) and shallow terrace (middle) on the edge of the Vona Vona Lagoon. There are two trial seaweed farms visible to the west and north of the lagoon.

Figure 36. Photo-mosaic from drone (UAV) photogrammetry overlain on Worldview-2 satellite imagery at Sageraghi showing location of GoPro video transect through a previous seaweed farm (Vavia 2018).

Figure 37. Aerial drone image (upper) contrasted with satellite image (lower) at Boe Boe 2, site of a previous floating longline trial.

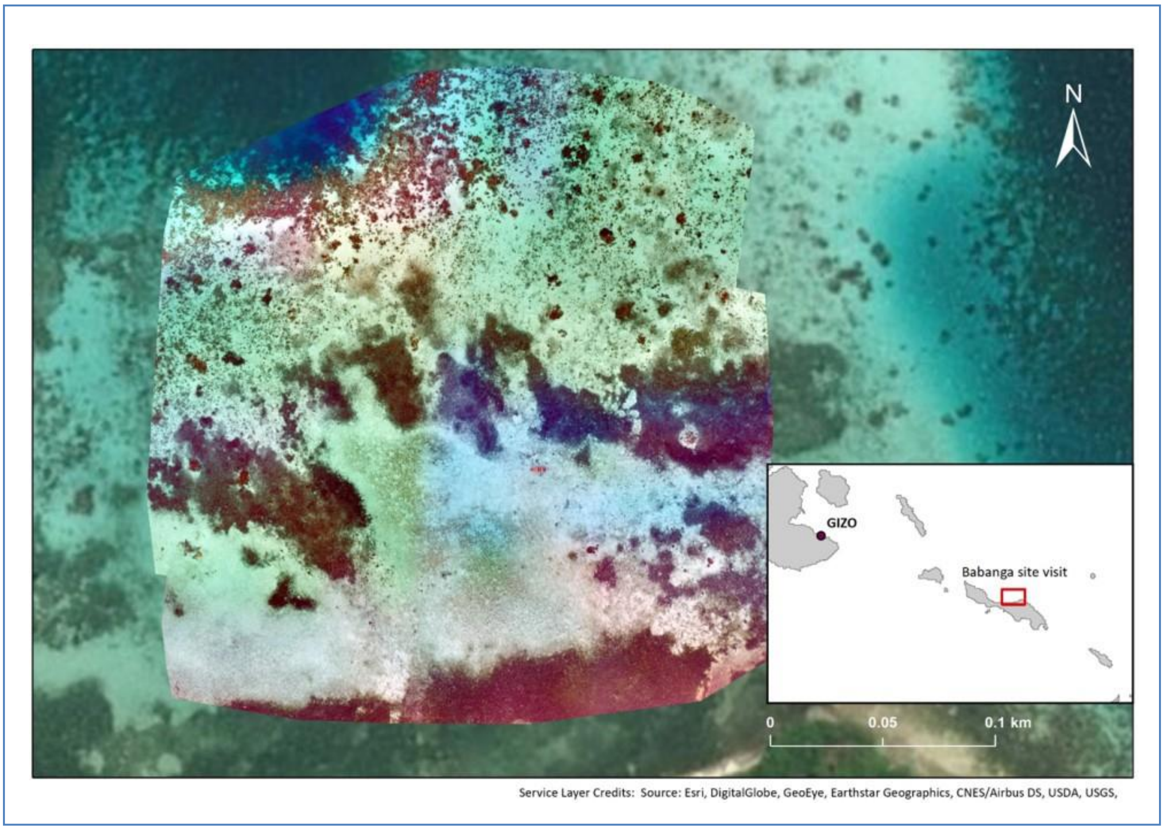

Figure 38. Photo-mosaic from UAV drone overlaid on WorldView-2 satellite image at a previous farm site near Babanga.

Figure 39. Section of a drone photo-mosaic of previous single floating line near Logha showing boulder corals and other outcrops on sand.

Figure 40. Seagrass and Halimeda algae on seabed at Sageraghi.

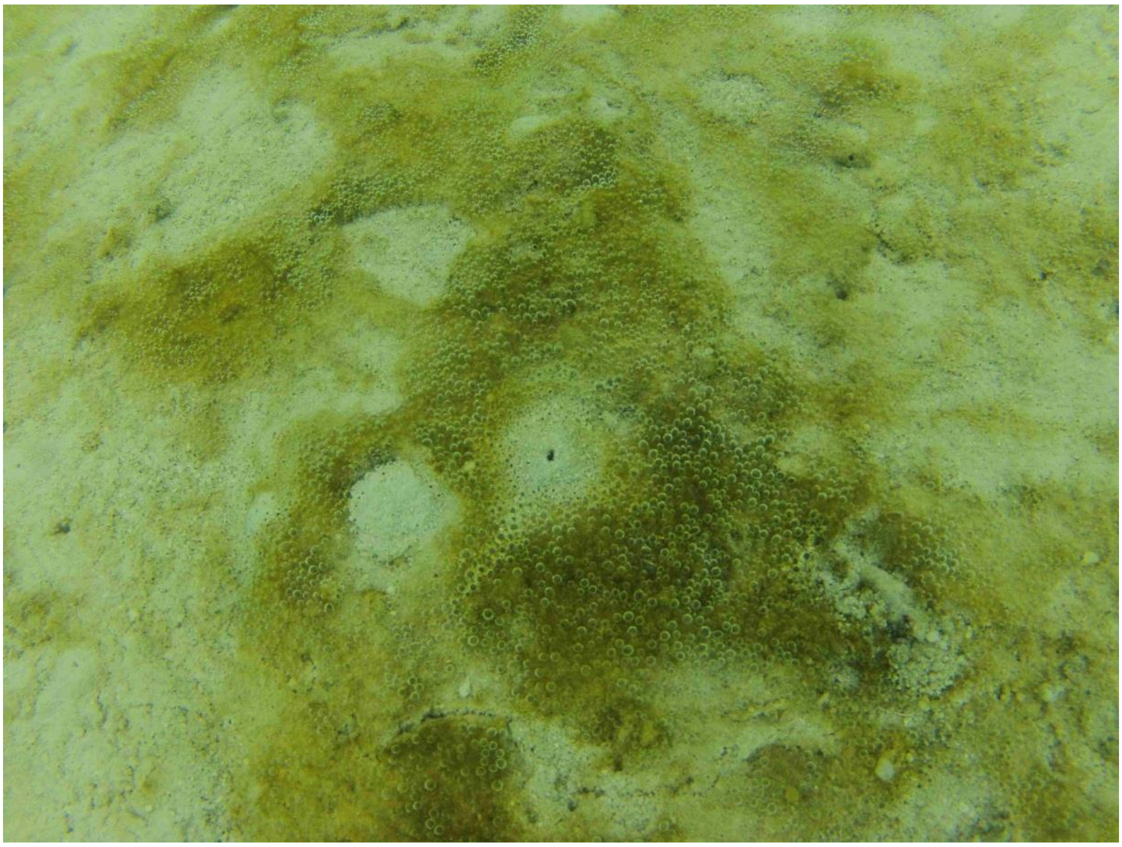

Figure 41. Algae with trapped gas bubbles on seabed at Sageraghi.

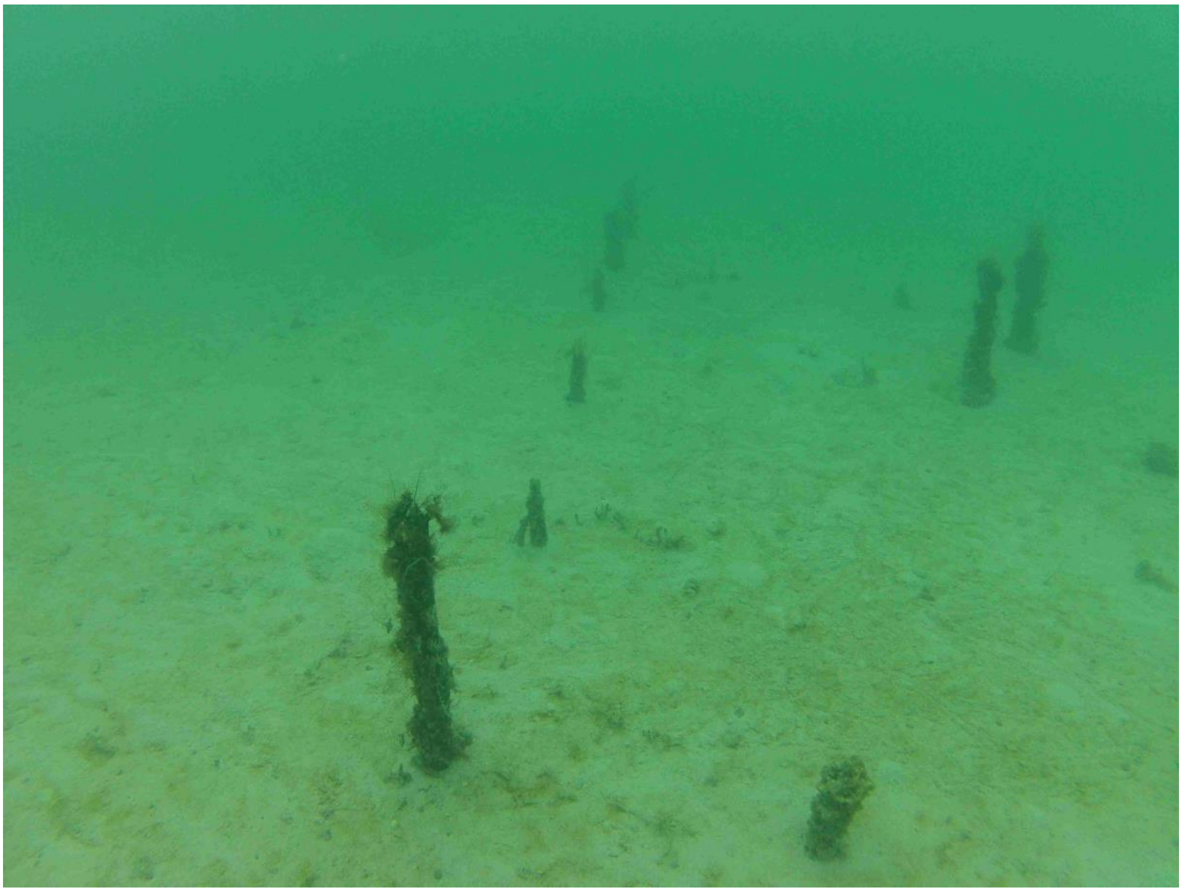

Figure 42. Posts from previous seaweed farm at Sageraghi.

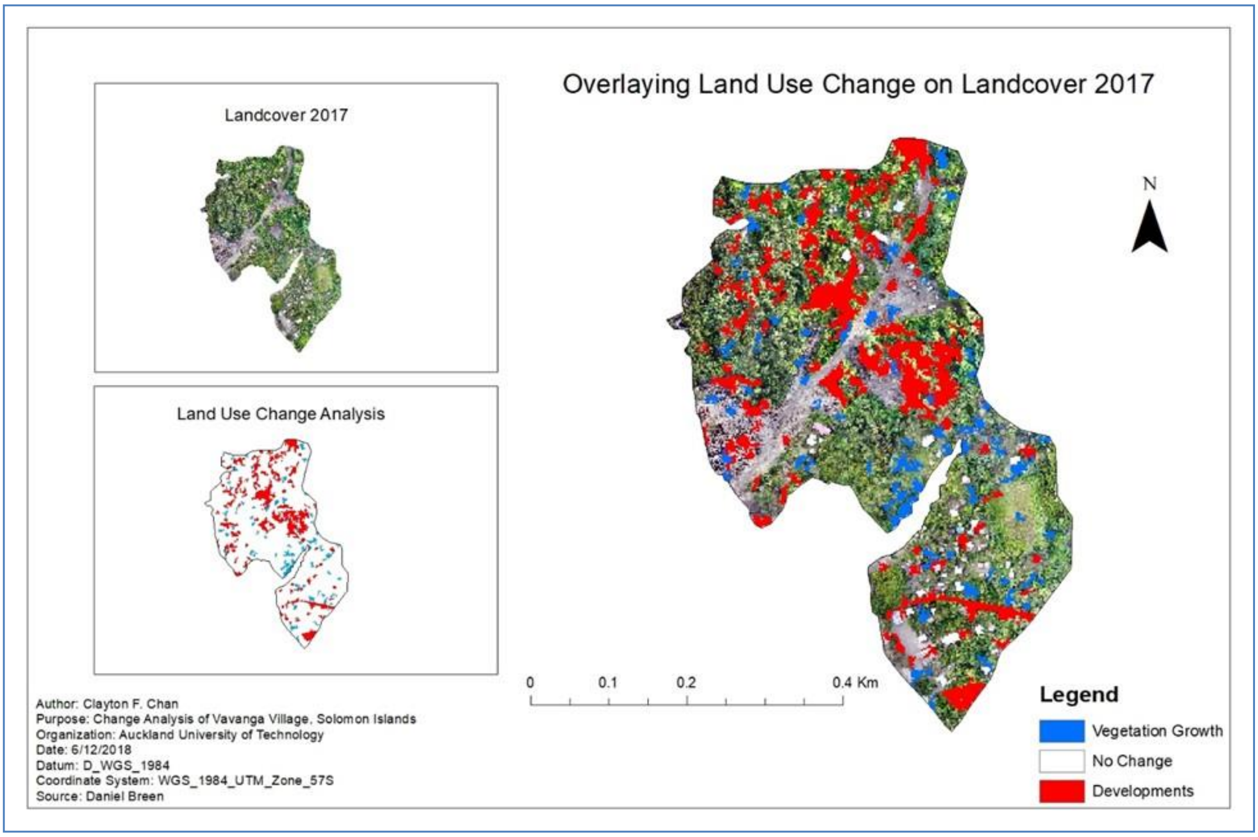

Figure 43. Change detection of coastal habitats at Kolombangara Island from UAV drone photo-mosaics flown in 2017 and 2018 (Chan 2018). Other data show the adjacent distribution of reef habitats and flood plumes from the river crossing these areas

4 Discussion

Decisions in environmental management and the use of natural resources are complex and context dependent. Detailed spatial information is rarely collected specifically to address these issues and best approximations are often derived from data intended for other purposes. What matters though, is whether data are fit for purpose and this will vary with the situation and how users evaluate the relevance and credibility of the source. Data analyses alone are poor substitutes for the subtleties of human judgement. The information tools presented here are intended as an aid to support not replace human decision making. There is a deliberate focus on data exploration rather than confirmatory analyses with a primary objective to help inform and engage stakeholders in participatory management. We illustrate some preliminary analyses and make some broad observations but the intention is for managers and stakeholders to use the tools and their own judgement as an integral part of the process. The intention is also to provide a foundation to add new information from other GIS and non-spatial data, remote sensing, literature, analysis and anecdotal knowledge from scientists, managers, stakeholders and the community.

The project was fortunate to have managers and consultants with regional knowledge of seaweed farming in the Solomon Islands on the research team. Some of this knowledge, in a rudimentary form, was successfully included in databases. There was also some consensus on broad patterns in environmental, social and economic influences on farm suitability, and many potentially viable locations for seaweed farming were identified. The extent of potential farm sites was also evident from the large areas of shallow terrace habitats mapped in the Millennium Coral Reef Mapping Project (IMaRS-USF, 2005). “Shallow terrace” was the dominant habitat mapped within identified seaweed farm sites. It is recognisable on satellite and drone imagery as those shallow sandy areas on the edge of sheltered lagoons. Though shallow, these areas are likely to retain some depth of water during low tides and may therefore be suitable for the off-bottom method of seaweed farming. There are hundreds of square kilometres of shallow terrace habitat spread throughout all provinces of the Solomon Islands, with the greatest area in the Western Province.

All areas may not however, be suitable for seaweed farms. Habitats mapped from satellite images, although of a relatively high resolution, may not always distinguish sand from other substrata and habitats are often a complex mosaic of different substrata and marine life. Other factors such as water movement and temperature are also critical for seaweed growth and ultimately, economic and social factors are probably the primary determinants of whether a farm succeeds.

We made simple estimates of the relative importance of these variables and their values at over 30 potential or existing seaweed farm sites using expert judgement from managers and measures describing the geographic relationships between farms and surrounding environments, infrastructure and people. Multivariate ordinations and cluster analyses indicated that while physical factors like depth, substratum and water movement were critical, there were important differences between sites for combinations of other factors like fuel, distance to village and alternative sources of employment. However, their influence on farm suitability is likely to vary markedly with location, time and other factors difficult to control or predict, such as international seaweed prices.

Malczewski (2006, 2010) reviewed the increasing interest in the use of GIS and multiple criteria analysis from as early as 1990. Cabral et al. (2016) assessed the use of a GIS integrated with a multiple criteria analysis to quantify compensation costs for seaweed farm installations in France. It included socio-economic and biophysical indicators in decision-making processes and considered the concerns of local communities with effects on other industries, recreational use and marine ecosystems. Sousa et al. (2012) identified sites for seaweed farming in Brazil from multiple criteria. The criteria used were mainly distances to markets and other features, unlike the study by Gimpel et al. (2015) where criteria were based on physical and chemical measurements.

Buitrago (2005) used a GIS to select sites for oyster aquaculture in Venezuela. It employed 35 experts to evaluate criteria in a multiple criteria analysis. Variability among the opinions of the experts was surprisingly large for factors such as bathymetry, use conflicts and tidal range. Nath et al. (2000) described subjectivity among experts when addressing weightings and warned that decision support tools cannot alone be used to completely facilitate decisions, but should rather be used to stimulate discussion in conjunction with other analyses, maps, human intuition, ethics, knowledge, consensus and experimentation.

The multiple criteria analysis tool used in this project integrated most of the data from the GIS databases and expert scores within one hierarchical model. It allowed alternatives (in this case farm sites) to be quantitatively assessed against a range of specific criteria according to user-defined weights. One advantage of the approach is that it standardises data to similar scales so that data from different sources, formats and measurement units can be directly compared. The results presented here are simplified examples, but the main strengths of the tool are realised through an interactive approach with users able to incorporate their personal knowledge, opinions and intuition. The software also provides for other models to be built for other kinds of planning and evaluation wherever there are alternatives and criteria involved.

The underlying databases also provide a foundation for other analyses and decision support tools. We provide a directory of additional free decision support tools including EMDS 6.0 (Environmental Management Decision Support. https://emds.mountain-viewgroup.com/), Marxan (Game et al. 2011) and Marzone (http://marxan.org/), Zonation (https://www.helsinki.fi/en/researchgroups/digital-geography-lab/software-developed-in-cbig), NatureServe Vista, (http://www.natureserve.org /conservation-tools/natureserve-vista) and PAST statistical software (https://folk.uio.no /ohammer/past/). There is considerable potential to apply these kinds of decision support to other applications in marine resource management in the Solomons and elsewhere (Breen et al. 2002, 2004; Fernandes et al 2005, 2009, 2010; Kerrigan et al. 2010; Breen 2011; Game et al. 2011).

In addition to planning for the economic and social benefits of seaweed farming, there is a need to assess the potential environmental and social consequences of seaweed farms. For this reason, data on seagrass, mangrove, marine protected areas and other managed areas were included in the QGIS project and in the proximity analyses. Additional information on vulnerable ecosystems from other data sets, anecdotal knowledge and literature (e.g., Green et al., 2006; Lauera and Aswanib, 2008; Albert et al., 2010; Roelfsema et al., 2013; Roelfsema, Phinn, et al., 2013) could also be mapped and incorporated in decision support tools including those designed specifically for conservation assessments, such as Marxan, Marzone (zoning for multiple use) and Zonation.

Decision support tools can also incorporate information monitoring the growth and administration of aquaculture activities. We digitised boundaries of seaweed farms around Wagina Island in ArcGIS from WorldView-2 satellite images. This information contributes to a better understanding of site suitability and may be useful in the planning and administration of new farms and permits. Challenges here include the cost of high-resolution satellite imagery, atmospheric interference, and the periodic (but ongoing) availability of data.

One of the limitations addressed in a recent review by Ottinger et al. (2016) is the spatial resolution of satellite sensors for identification of single aquaculture sites, as the sites can be relatively small. Dean and Salim (2013) noted that getting access to such data means contacting suppliers of satellite derived data and that one of the issues with collecting and compiling data for spatial analyses is that although data may exist at national levels, the data processing can be both expensive and time consuming. The data sets that are freely available may have coarse resolutions but can, however, be fit for purpose. Pasqualini et al. (2005) found their 10 m resolution map was 73 % accurate, and their fine-resolution 2.5 m maps were 96 % accurate. The need for accuracy depends on the nature of the research, and what ecological and social information is considered necessary.

More detailed aerial photography at specific sites can be obtained from UAV drones and software that combines hundreds of individual photos into georeferenced photo-mosaics and topographic models. In addition to being high resolution and low cost, drone photography has the advantage of being able to strategically target specific times and locations. We used a small, off-the-shelf DJI Phantom4 quadcopter to successfully survey five sites including a small trial seaweed farm and several previous farm sites. These photogrammetry tools have many applications in the seaweed farming industry and in other natural resource management.

High spatial resolution imagery is useful but data for turbidity, sea surface temperature, water quality and other variables are also desirable (Dean and Salim, 2013). However, wave action, winds and currents mean that such measurements can be highly variable, and although long term averages can be used, the spatial scale is often coarse relative to farm size.

Challenges that limit the growth and development of the seaweed industry in the Solomon Islands stem from multiple sources, many of which may not be readily described in a GIS. Some economic and social criteria for site suitability were assessed by expert judgement and very approximate geospatial measures. However, some of most important economic determinants of seaweed farming success operate at a national or international level.

One of the main issues for the Pacific Islands is the small contribution they make to global production, and the distances to markets and ports. Compared to Asian seaweed cultivators, the Solomon Islands and other Pacific producers struggle within the carrageenan market. A shortage of international buyers for Pacific seaweed has limited the overseas market and growers and exporters are forced to accept lower price negotiations (McHugh, 2006; Kronen, 2013).

Valderrama et al. (2015) found that remote places like the Pacific have difficulty because of their lack of proximity to processing centres and their low market power due to relatively low production and increasing fuel costs for shipping. McHugh (2006) noted the instability of farm gate prices that may result from fewer farmers or seaweed shortages resulting from natural disasters.

International market prices are dependent on the quantity and quality of product supplied, as well as the demand and structure of the market. Producing low quality seaweed results from poor handling post-harvest, having sand and plastic materials mixed with the seaweed, high moisture content and low carrageenan yields (Trono and Lluisma, 1992). The farm gate prices are determined by the buyers and dependent on the international markets (Msuya, 2006).

It is important for Pacific Island countries to be producing seaweed of a higher quality and consistent output to stabilise their position in the market, as the market for carrageenan should tend to expand if the demand continues to grow (Cai et al., 2013). Pickering (2006, 2007) stated that seaweed farming easily competes with copra, agriculture and fishing as a source of revenue, although not with revenues received from logging. Seaweed farms can benefit from employing local communities and families but fluctuations in the price of seaweed can drive workers to more profitable industries.

While seaweed farming in the Solomon Islands is less extensive than in Asia and other regions, growth in the extent of farms has been strong (FAO, 2014) and there is much potential for farming in other parts of the Pacific. An ability to identify potential farming areas and anticipate planning issues using tools such as those described here can help ensure that such growth is sustainable.

5 Conclusion

This study reveals substantial opportunities for the sustainable development of seaweed farming in the Solomon Islands but these need to be considered in conjunction with social and economic values and local knowledge and experience.

Discussions of farming techniques, the responses of seaweed cultivars to abiotic and biotic influences and economic influences on the industry (Trono, 1990; Trono, 1992; Hurtado et al., 2001; Pickering, 2006; Reis et al., 2017) indicate that there is potential to develop the seaweed industry in the Solomon Islands within its extensive shallow, sheltered, clean coral reef, island and lagoon systems. Many rural coastal communities scattered through the islands already rely on marine and other diminishing natural resources (Kronen, 2013) and there is an impetus to introduce opportunities for sustainable employment and income, especially when employment in other more extractive industries such as forestry, mining and fishing may be less sustainable.

GIS-based decision support tools can integrate data from many different sources, formats and fields of research and interactively display realistic representations of complex environments at many spatial scales in an intuitive visual format. They provide a useful focus for aquaculture policy and participatory planning, including workshops with managers, communities and other stakeholders. This project is another step in enabling a strategic and inclusive approach to planning for sustainable aquaculture in the Solomon Islands and the Pacific region.

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Appendix 1. Key institutions and individuals consulted for this project

The team met with several management staff at the Ministry of Fisheries including the Deputy Directors, Ms. Rosalie Masu (Inshore Fisheries) and Ms. Ronnelle Panda (Policy, Planning and Project Management), the Chief Fisheries Officer, Mr. Sylvester Diake and research collaborators, Mr. Wesley Garofe (MFMR seaweed farming) and Mr. Sebastian Misiga (GIS analyst) accompanied us to locations in the Western Province where seaweed farms had previously been trialled and provided input on factors influencing the success of farming and existing sources of spatial data and geospatial software.

Discussions were also held with a consultant for the Ministry of Fisheries, Mr. Mahuri Robertson and Rarumana seaweed farming agent, Mr. Lamu Vara Livingstone. Discussions with Fisheries staff and consultants and existing GIS data were used to map and update existing and previous sites for seaweed farming and assess the suitability of these sites according to different physical, biological and social variables.

List of institutions consulted:

- Solomon Islands Ministry of Fisheries and Marine Resources (MFMR)
- Gizo Fisheries Office (MFMR)
- Mekem Strong Solomon Island Fisheries (MISSIF)
- Solomon Islands Government ICT Support Unit
- Rarumana Seaweed Farming
- Solomon Islands National University (SINU)
- University of the South Pacific (USP)
- The Pacific Community (SPC) Sustainable Aquaculture Development project
- New Zealand Ministry of Foreign Affairs and Trade (MFAT)
- New Zealand High Commission
- New Zealand Institute for Pacific Research (NZIPR)
- Auckland University of Technology (AUT)
- University of Otago.

List of individuals consulted:

- Solomon Islands Ministry for Fisheries and Marine Resources Head Office (MFMR)
  - Ms. Rosalie Masu – Deputy Director, Inshore Fisheries
  - Ms. Ronnelle Panda –Deputy Director – Policy, Planning and Project Management
  - Mr. Sylvester Diake – Chief Fisheries Officer, Head of Aquaculture
  - Mekem Strong Solomon Island Fisheries (MSSIF)Dr. Anne-Maree Schwartz – Director
  - Dr. Ruben Sulu – Aquaculture Consultant
- Solomon Island Government Information Communication Technology Support Unit (ICTSU)
  - Mr. Smith Iniakwala – Director
  - Mr. Steve Erehiru – Deputy Director (Strategy and Planning)
- New Zealand High Commission, Honiara, Solomon Islands
  - Mr. Steve Hamilton, First Secretary (Development), NZ High Commission, Honiara.
- Solomon Island National University (SINU)
  - Prof. Prem P. Rai – Dean of School of Natural Resources and Applied Sciences (SNRAS)
  - Mr. Alex Makini – Head of Environmental Sciences, SNRAS
- University of the South Pacific (USP)
  - Dr. Patricia Rodie – Director Honiara Campus
  - Mr. Primo Ugulu –Geography Dept, Honiara
- Gizo Fisheries (MFMR)
  - Mr. Kolo Hivu – Fisheries Officer
- Rarumana Village – seaweed farmers
  - Mr Lamu Vara Livingston – Village spokesperson
- Triland Trading
  - Mr Mahuri Robertson