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Adaptation strategies for coral reef ecosystems in Small Island Developing States: Integrated modelling of local pressures and long-term climate changes

M. Hafezi [a, b], O. Sahin [a, b, c, *], R.A. Stewart [a, b], R.M. Connolly [c, d], B. Mackey [c], D. Ware [c, e]

[a] School of Engineering and Built Environment, Griffith University, Gold Coast, QLD, 4222, Australia
[b] Cities Research Institute, Griffith University, Nathan, QLD, 4111, Australia
[c] Griffith Climate Change Response Program, Griffith University, Gold Coast, QLD, 4222, Australia
[d] Australian Rivers Institute – Coast and Estuaries, School of Environment and Science, Griffith University, Gold Coast, QLD, 4222, Australia
[e] Griffith Centre for Coastal Management, Griffith University, Gold Coast Campus, Queensland, 4222, Australia

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A B S T R A C T

Planning and decision-making vastly benefit from a holistic and systematic understanding of the long-term impacts of climate change and other non-climatic stressors on the health and resilience of coral reef ecosystems, and the efficacy of adaptation strategies and management interventions on mitigating these impacts and maintaining ecosystem condition and associated ecosystem service. This study reports on an approach to modelling coral reef stressors and possible adaptation interventions using the coral reef ecosystem of Port Resolution on Tanna Island, Vanuatu as the case study serving as a microcosm of endangered Pacific Small Island Developing States (SIDS). A novel participatory modelling framework was developed and followed in a stepwise manner to integrate local and long-term climate change pressures by coupling structural analysis and the Bayesian Network (BN) techniques. The BN model was quantified through an advanced consolidated data-induced, evidence-based, and expert-driven approach that incorporated: (1) projections of future climate conditions and changing human activities; (2) the influences of multiple stressors including physical environmental and sociological factors; and (3) spatial variability in the key processes and variables. The first and second phases conceptualised the whole system by providing a graphical presentation of system variables within the Driver-Pressure-State-Impact (DPSI) framework using the structural analysis technique. In the third phase, the BN technique was used to integrate the outcomes of multidisciplinary assessments and analysis with experts' opinion. The BN modelling phase was completed based on evidence extracted from literature which reported the results of regional and downscaled climate models, GIS-based analysis, parametrised data obtained from the region, and tacit knowledge elicited from experts. The validated model was employed to anticipate the future health and resilience condition of coral reefs under different sets of climatic trajectories and adaptive responses scenarios. The results predict the risks to the health and resilience of the Port Resolution coral reef system from the adverse impacts of climate change and harmful human activities and the possible success of adaptations strategies. A sobering conclusion was that despite the current satisfactory condition of coral reefs in the case study zone, their health and resilience would be severely threatened by 2070 in the absence of implementing adaptation strategies and associated sustainable management interventions.

1. Introduction

Global population growth and increasing human impacts on ecosystems raise questions around the functionality and capability of marine ecosystems to provide adequate services which support social wellbeing to an acceptable level (Santos-Martín et al., 2013).

* Corresponding author. School of Engineering and Built Environment, Griffith University, Gold Coast, QLD, 4222, Australia.
E-mail addresses: mehdi.hafezi@griffithuni.edu.au (M. Hafezi), o.sahin@griffith.edu.au (O. Sahin).

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Variations in the functioning and composition of marine ecosystems and the resultant threats and opportunities of ecosystem changes can significantly affect human well-being (IPCC, 2014). According to the Millennium Ecosystem Assessment (MEA, 2005), in many instances, the flow of ecosystem services is being impaired as a direct result of changing climate conditions as well as non-climatic pressure. Within several decades, this current trend will result in the alteration of all ecosystems and may have severe negative impacts on ecosystem services and human well-being (Colls et al., 2009). Therefore, it is of paramount importance to identify, assess, and understand the provision of ecosystem services, to put more planning efforts toward improving the health and resilience of the supporting ecosystems. However, recommending management strategies or adaptation planning should incorporate the uncertainties in future social and natural land conditions under different climate change pathways (Comte and Pendleton, 2018).

Small Island Developing States (SIDS) are among the most vulnerable communities, being highly dependent on services from coastal ecosystems. SIDS are a group of 57 small island countries listed by the United Nations Department of Economic and Social Affairs (UNDESA) (Spector et al., 1994) that share similar sustainable development challenges despite specific cultural and geographical differences (Hay, 2013). A range of factors, namely, remoteness, limited public education services and community awareness, being highly exposed to natural extreme events and disasters, and limited accessible funds are considered the most important challenges for SIDS. Inopportunely, coral reefs are also particularly vulnerable to multiple local-based activities and pollution, and climatic distresses (Hughes et al., 2017; Ateweberhan et al., 2013). Globally, coral reefs provide services and livelihoods for millions of people (Hughes et al., 2017). For SIDS in particular, coral reefs are among key ecosystems for sustaining livelihoods (Martin et al., 2017) and, together with mangroves, important for coastal protection against extreme weather events (Hughes et al., 2017). Thus, planning for SIDS communities under rapidly changing and uncertain non-climatic and climatic conditions requires a realistic and long-term evaluation of impacting factors and potential management interventions for minimising the risks to these ecosystem services and that are effective and appropriate (Betzold, 2015; Robinson, 2017). Tanna Island, Vanuatu, was selected as a case study region since it represents a typical microcosm of Pacific-SIDS geography and human settlements that are highly reliant on ecosystem services. It is to be noted that this study was undertaken as a part of an extensive project titled “EcoAapt in the Pacific” that aimed to identify appropriate adaptation interventions in the coastal zones of Pacific island states and territories in the face of rapidly changing climate and ongoing capital-intensive developments.

However, assessments of erratic, multidimensional and complex systems, such as coral reef ecosystems (Harvey et al., 2018) that exhibit a high level of uncertainty (Hoegh-Guldberg et al., 2019), mandates the employment of an integrated approach (Hafezi et al., 2018). Moreover, each assessment requires a customised procedure that can cater to the specific needs and characteristics of each system (Voinov and Shugart, 2013). Particularly, environmental systems, which are under constant changing climate conditions, are more likely to yield reliable outcomes when an integrated modelling approach is exploited (Hafezi et al., 2018). Besides, assessments of the socio-economic components of the coral reefs’ health and resilience system, as well as region-specific characteristics, opportunities, and limitations mandate the elicitation of local stakeholders’ knowledge in conjunction with other inputs, in order to derive reliable equations and probability distributions (Hoegh-Guldberg et al., 2019). Accordingly, this study required a modelling approach that is capable of taking into account the following aspects: 1) multiple factors that are conventionally dealt with by different disciplines but that account for a wide range of climate change-induced risks, and an assessment of the central ecosystem; 2) integrative evaluations that combine both quantitative and qualitative types of data; 3) understanding of the causal relationship between the multiple stressors and reef health and resilience; and 4) effective treatment of the modelling complexities and uncertainties associated with the array of social and environmental factors. In other words, adoption of an advanced and practical approach and strategy was a mandate rather than an option to incorporate different types of qualitative and quantitative multidisciplinary data as well as to include a proper description and quantification of uncertainty in the modelling and assessment processes. For this purpose, an innovative participatory and integrated modelling strategy was to be developed that is highly efficient in integrating local and long-term climate change pressures under the specific characteristics of SIDS.

Recently, the Bayesian Network (BN) technique has gained researchers attention (Kerebel et al., 2019) and been employed as the main modelling platform in different environmental studies such as ecosystems and ecological assessments (Smith et al., 2018), water management (Hallouin et al., 2018; Phan et al., 2016) and ecosystem services modelling (Zeng and Li, 2019). Landuyt et al. (2013) conducted a SWOT analysis of modelling techniques for ecosystem services and suggested the BN methodology as well suited for ecosystem-related assessment, despite some limitations and weaknesses. Similarly, Uusitalo (2007) identified the BN as an effective approach for complex environmental modelling and management problems having high specificity requirements. However, the key attributes for an adequate assessment of coral reefs health and resilience necessities the BN model to be quantified using multidisciplinary, data-induced, evidence-based, and expert-driven approaches. In light of these requirements, this study requires to further advance previous BN modelling frameworks for reef management, such as Gilby et al. (2016) and Brown et al. (2017), by integrating long term climate scenarios with local pressures from increasing human use and land-management. Additionally, the exploitation of structural analysis in a sequential integration procedure coupled with other modelling techniques in a stepwise manner enables modelling needs and requirements to be addressed more effectively (Suprun et al., 2018).

This paper presents a novel probabilistic scenario-based modelling approach using hybrid exploitation of the BN and structural analysis techniques using qualitative and quantitative data to investigate the long-term impacts of climatic and non-climatic pressures, together with a range of management response strategies, on the health and resilience of coral reefs for the time horizon of 2070. While the resilience of coral reefs represents the recovering capability of reef systems to recover towards a coral-rich state from either climatic or non-climatic pressures disturbance as a result of extreme events (Hughes et al., 2017). In addition, reef system resilience can be referred to their resisting or maintaining capacity against shifting from the morphological diversity towards single coral morphology or algal dominance (Scott et al., 2015). However, the health and resilience of coral reefs is relative to the coral cover in the study zone in this study. The Representative Concentration Pathways (RCP)s (IPCC, 2014) were used as the basis for different climatic scenarios to explore the implications of climate change impacts.

2. Case study location

Tanna is a relatively small island (550 km^2) in Tafea Province, State of Vanuatu (in the Melanesian Pacific islands), in the South

Pacific Ocean, with a rapidly increasing population largely living in traditional village communities (Buckwell et al., 2019). (Elliff and Kikuchi, 2017). Coral reefs are subject to multiple anthropogenic pressures, which currently deliver vital ecosystem services to Tanna's community, including improving the local economy through tourist attraction (Mackay et al., 2019); fish habitat and food supply; protecting local territories Spalding et al., 2014 through sand production and protecting the coastlines from coastal erosion (Sahin et al., 2019); promoting human health condition through food supply (Elliff and Kikuchi, 2017); and supporting the local traditional culture, known as Kastom across Melanesia (Buckwell et al., 2019; Mackey et al., 2017). The current population of Tanna based on the 2016 census, is around 32,000 (UNDESA, 2017). Tanna Island has a diverse ecosystem with tropical forests, grasslands, water bodies, and diverse marine ecosystems, as shown in Fig. 3. The coral reef is by far the most common ecosystem along the Tanna coastline, with occasional seagrass meadows, mangrove forests and sandy beaches (SPREP, 2016b). According to a recent valuation of ecosystem services (Mackey et al. (2017), more than 80% of Tanna Island's ecosystem services are currently being provided by coral reefs. While, subsistence gardening provides around 18%, and other ecosystems can only provide around one per-cent of the valued services.

Recent surveys of Tanna's coral reefs show that the reefs located in the Port Resolution generally have moderate levels of both coral cover and fish populations. At our focal area of Port Resolution, fishing pressure is considered moderate and localised according to the latest surveys, but there are reports of diminished stocks of harvested species of fish and invertebrates (Mackey et al., 2017). Port Resolution, therefore, provided a useful case study for exploring an integrated modelling approach to test management scenarios on known and predicted climatic and non-climatic pressures on a time horizon of 2070.

3. Modelling approach

The modelling approach and procedure were formulated by the multidisciplinary team of experts having skillsets from diverse and independent research fields including marine biology, coastal systems, climate change, systems modelling and risk assessment. Importantly, it should be noted that these experts had adequate knowledge of the study area and context since they were previously involved in a research project focusing on climate change resilience analysis and ecosystem and socio-economic mapping of the country of Vanuatu as reported by Buckwell et al. (2019), Sahin et al., 2019, and Mackey et al. (2017). To fulfil the modelling requirement of this study, a modelling procedure was developed that uses a stepwise iterative approach incorporated expert knowledge (Fig. 1). This procedure comprises three main phases, including i) Research/model delineation; ii) Model conceptualisation; and iii) Bayesian Network (BN) Modelling. As the major part of the conceptualisation phase, the causal interrelationships between factors were mapped conceptually throughout different expert workshops using structural analysis as followed by Eker and Zimmermann, 2016 and Suprun et al. (2016). Next, the BN modelling procedure was followed based on the findings of the previous phases. Subsequently, the scenario-based analysis of modelling results was conducted to evaluate the efficacy of adaptation strategies for coral reefs ecosystems under different future climatic and non-climatic conditions. Each phase comprises different steps as detailed in Fig. 1, in which, iterations of previous phases or steps if required.

The BN modelling technique has been used in the literature somewhat differently to model coral reefs, including Brown et al. (2017) focused mainly on the impacts of water quality on coral reefs using a BN model; Ban et al., 2015 predicted ecological reef conditions in response to different management options without considering the impacts of climate change in its BN model; Franco et al. (2016) used BN techniques impacts of land and marine-based pressure without considering the impacts of management intervention; Ban et al. (2014) developed a BN model by utilising formal expert-elicitation processes in the absence of data-driven quantification approaches to obtain estimates of modelling outcomes; Renken and Mumby (2009) conducted the BN modelling of resilience of coral reefs to biological disturbance only, specifically Macroalga, in the case of Glovers Reef, Belize in Central America; and lastly; Wooldridge and Done (2003) studied the associations of coral mortality and events bleaching using both empirical data and experts' knowledge which was further developed by adding a GIS-based analysis to the model (Wooldridge and Done, 2004).

In this study, the limitations of BN modelling were mitigated through the integration of GIS-based assessments and structural analysis throughout a systematic stepwise procedure. This study has adopted an advanced fully integrative BN approach to model climatic, local and marine-induced pressures as detailed in the next section.

3.1. Bayesian network (BN) approach

BNs fall into the category of probabilistic graphical types of tools capable of handling decisions under uncertainty (Peng et al., 2018).

Equation (1) presents the basic Bayes' theorem:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad \text{Eq. 1}$$

where both P(A) and P(B) are the probabilities of observing A and B without regard to each other; P(A|B) is the conditional probability of A, given B; P(B|A) is the conditional probability of B, given A; and P(B|A)/P(B) is the likelihood ratio or Bayes factor. A BN model presents different events or variables with their dependencies (showing their relationships and the associated conditional probabilities) to calculate the probabilities of various possible causes Onyango et al., 2016. BNs are typically composed of three main elements: (1) a set of variables known as nodes; (2) arrows to represent the hierarchical relationship between variables (i.e. DAG); and (3) conditional probability tables (CPT)s or input functions or equations to calculate the state of variables through the constructed probability distribution (Rahman et al., 2015). Having all nodes mapped in the final DAG, states of nodes were initiated to be described individually. Each state should represent a possible real-world condition of a node in the time horizon of this study (i.e. 2070). Generally, nodes' states should be mutually exclusive and finite in number and capable of being parameterised as either categorical, Boolean, continuous or discrete (Landuyt et al., 2013). The setting of discrete intervals should follow a rational and explicable process to achieve a representative and robust model (Pollino et al., 2007).

4. Modelling procedure

4.1. Delineation

Formation of the modelling team, formulation of the modelling approach and the definition of modelling scope including regional, temporal, and interdisciplinary boundaries were established throughout the delineation step. An extensive review of the literature on coral reef health and resilience was conducted to identify the key variables and stressors (see Supplementary File A).

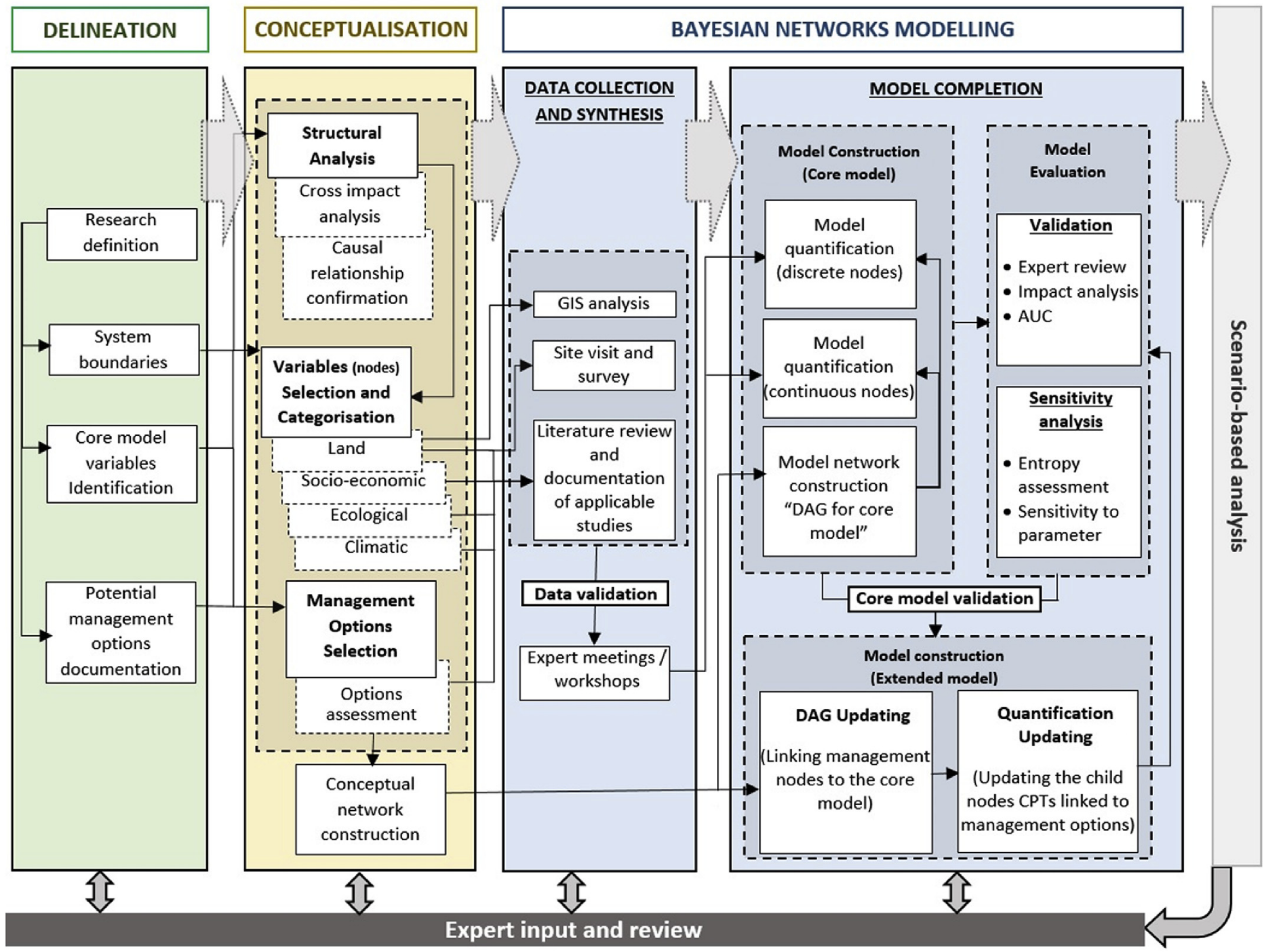

Fig. 1. Modelling stepwise procedure
(GIS: Geographical Information Systems, DAG: Diagram of Acyclic Graph, CPT: Conditional Probability Table, AUC: Area Under Curve).

Following this, a list of 23 key variables was selected from a list of variables (known as nodes in BN modelling) through two expert workshops in late 2017. Subsequently, the experts were provided with a range of preliminary potential land and marine-based management options for improving the health and resilience of coral reefs extracted from an extensive literature review (see Supplementary File B). This list was later condensed in the next phase, whereby only those management options that were deemed compatible with the specific geographical and socio-environmental features of the study area were retained. Appropriate experts were consulted to ensure that only comparable evidence reported in the literature that linked individual management options to coral reef health resilience or improvements was considered. Our starting conditions for Port Resolution were based on a site survey in Nov 2016 by our expert team members showing a diversity of species of hard and soft corals, with occasional bleaching, and turf and crustose coralline algae. In developing the model, experts and system modellers paid particular attention to the conceptual understanding of reef ecology and vulnerability from other islands in the South Pacific (Brown et al., 2017) and from the Great Barrier Reef (GBR) on the east coast of Australia (Hughes et al., 2017b; Done, 1982).

4.2. Conceptualisation

This phase comprised of two major steps (1) documentation of the confirmed nodes; and (2) validation of system nodes relationships and development of a conceptual model. Nodes and their relations were initially constructed with the benefits of previously studied frameworks for coral reefs (Gilby et al., 2016; Brown et al., 2017), before confirming with experts via an acyclic causal diagram. Upon the completion of the documentation step (reported in Supplementary files A and B), the conceptual model was developed in a practical and relevant framework to environmental assessments to conclude with an adequate conceptual model to undertake the next phase (i.e. BN modelling).

The Driver-Force—Pressure—State—Impact-Response (DPSIR) is one of the most widely used frameworks in conducting environmental assessments, due its transparency, simplicity and ability to integrate multidisciplinary stressors and to direct the causal relationships of system variables (Argent et al., 2016). Gari et al. (2015) identified 79 articles that have applied the DPSIR framework individually or integrated with other tools/approaches studying on marine or coastal social-ecological systems. According to Gari et al. (2015), employing the DPSIR framework is an effective and appropriate approach for the assessment of management interventions addressing environmental concerns. However, the response layer in DPSIR refers to the responses of the model to the impact layer and generates feedback to the other four layers of the model (Argent et al., 2016). Accordingly, the response layer was not considered in the conceptualisation phase because of not being applicable given the scope of this study, and therefore, the nodes were categorised within the Driver-Pressure-State-Impact (DPSI) framework instead of DPSIR (Fig. 2). Subsequently, all nodes were clustered within a DPSI framework based on their nature and mechanism of impact as following: climatic nodes (driver); controlling or management and adaptation nodes (driver); land-based nodes (pressure); ecological and socioeconomic pressure nodes (pressure); coral lethal threats including bleaching, diseases, and physical damage nodes (state); the health and resilience of coral reefs as the target node (impact). See Supplementary File A for detailed definitions of each variable represented in Fig. 2.

The broad list of potential management options that was documented in the project delineation phase, and included structural, institutional, social, regulatory, and technological support potential options, was reduced to five options by the experts according to the region's specific characteristics, opportunities and limitations (as described in Supplementary File B). The concluded management options were added as management nodes in the DAG within the driver layer and were later linked to the core model nodes once the core model was validated as demonstrated in Figs. 1 and 2.

4.3. Bayesian Network (BN) modelling procedure

Development of the BN model required the inclusion of both qualitative assessments through the development of the conceptual models and the DAG, and quantitative assessments (i.e. parameterising the model with data by populating CPTs or equation-based techniques) (Phan et al., 2016).

4.3.1. Construction of the diagram of acyclic graph (DAG)

The final DAG model was developed based on the results of the previously taken steps in delineation and conceptualisation phases. There is often a trade-off between representing causal relationships and developing a model which has the minimum level of complexity required to provide robust, plausible and reliable performance. Applying a proper framework in the process of DAG construction can assist BN modellers in avoiding over-complexity of CPTs, managing the layers of DAGs effectively (Sahin et al., 2019), and controlling the sensitivity of the target node to the rest of the nodes if the BN has a single target variable (Aguilera et al., 2011).

4.3.2. Model quantification

Relative states were assigned to each node exclusively (continuous and discrete) to arrange the model for the scenario-based analysis upon the completion of the model quantification step. To compound misjudgements and to provide a mutual perception of the nodes' mechanism of impact among experts and system modellers, all nodes alongside with their states were documented and described thoroughly before any parameterisation or CPT completion (see Supplementary A).

Next, the relationship functions or CPTs of nodes were populated and finalised using different methods depending on the availability of data, the predictability of future condition of each

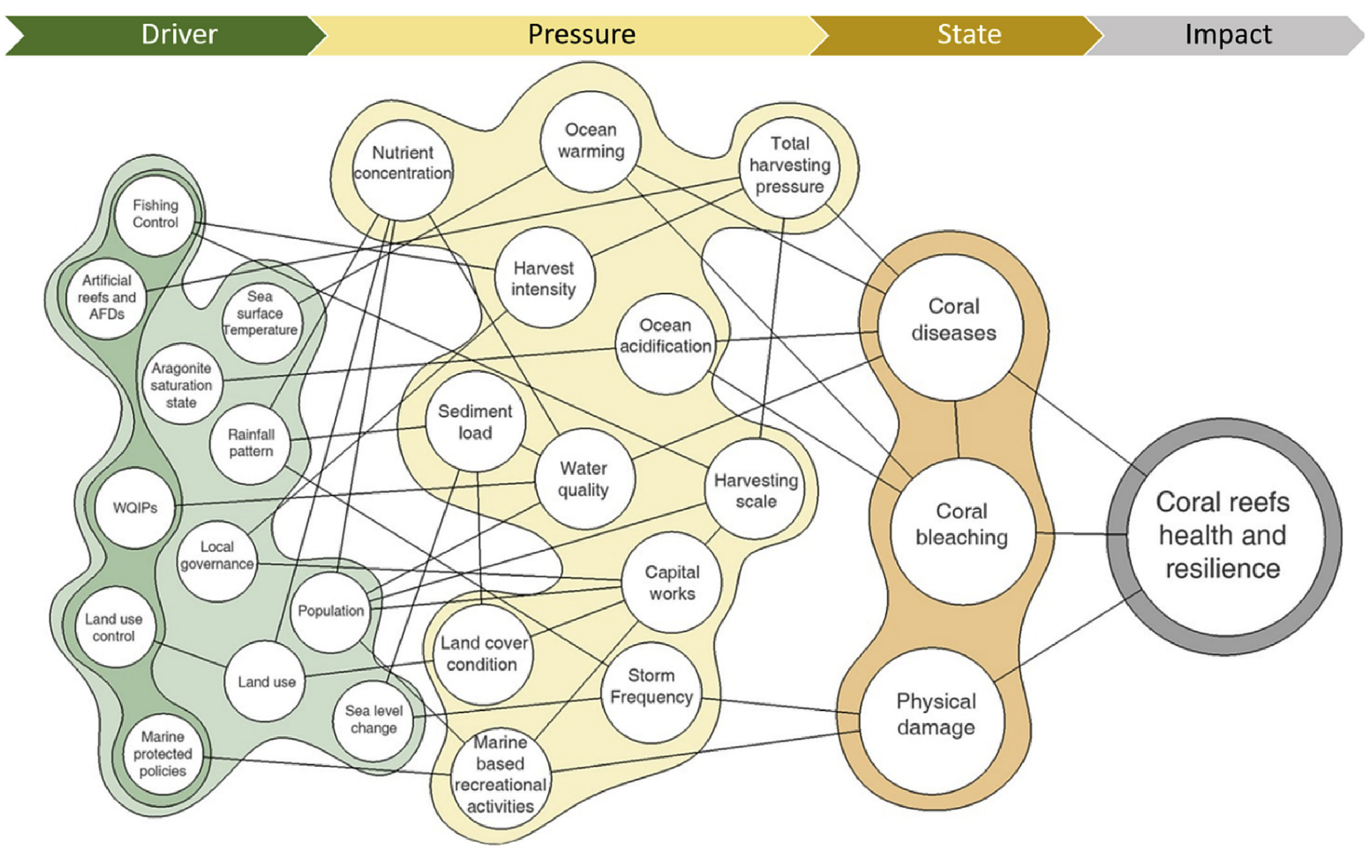

Fig. 2. Causal relationships of nodes within the DPSI framework
(management nodes: within dark green; other nodes of the driver layer: within light green; nodes within the pressure nodes: yellow; nodes within the state nodes: orange; the impact (target) node: grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

node's states, and the assigned group within the DPSI framework. A range of parametrisation methods was agreed and designated to each node in a workshop. Apart from the designated expert and stakeholder workshops, it should be noted that a series of regular meetings with the expert team were conducted to regulate and to supervise the modelling procedure (Fig. 1).

In summary, model quantification was accomplished through the following approaches:

- Data-induced from equations and probability distributions using the available downscaled modelling results (known as BN inductive learning process when sufficient numerical data is available as recommended by Pearl (1988));
- Synthesising knowledge and data based on the existing literature and studies only confirmed by experts; and
- Evidence-based and expert-driven CPTs learning that require adaptation of existing literature coupled with expert opinion.

The final DAG, consisting of the nodes with their states and the joint probability distribution over the nodes, was developed by NETICA software version 5.4 (Norsys Software Corp, 2009). (see Supplementary File C for the NETICA model). The quantification and CPTs completion methods with the references for different layers of nodes within the DPSI framework are detailed next.

5. Codifying layers and data collection

The following sub-sections outline the various nodes and supporting evidence used to quantify the model by completing nodes' relationship functions or CPTs within the four DPSI layers. Readers are referred to Supplementary Files A and B for a detailed discussion of the node definitions and supporting evidence.

5.1. Driver layer

5.1.1. Climatic nodes

The climate-related variations for the region of the study were projected depending on the selected future climate change scenarios linked to one of the four IPCC acknowledged GHG trajectories (known as RCPs). All climatic nodes were directly linked to the *climate scenario* node with all the four RCPs as its four different states. Consequently, the projections of the climatic nodes and its child nodes were produced using the documented findings of downscaled climate models in the literature, mostly based on the results of Coupled Model Intercomparison Project (CMIP)-based Global Climate Models GCM, as well as the outcomes of the other region-based studies based on the 20-year mean variations centred on 2070 relative to a 20-year period centred on 1995 reported by Alexander et al. (2018), Australian Bureau of Meteorology and CSIRO (2014), Stephens and Ramsay (2014), and Walsh et al. (2012) (see Supplementary File D). In other words, all probability distribution functions of variations of the climatic nodes (including the land temperature, the sea surface temperature, the ocean acidification, the rainfall pattern and the storm pattern nodes) were completed based on the mean projected variations from 2060 to 2079 (centred on 2070) relative to the recorded variations from 1986 to 2005 (centred on 1995) reported by different researchers in the selected references.

According to Alexander et al. (2018) and Australian Bureau of Meteorology and CSIRO (2014), the averaged trend of *sea surface temperature (SST)*, also known as ocean warming, is expected to continue varying between -0.2° and 3.2° degrees during the period of 1986−2099 with 95% confidence level for different RCPs. Despite diverse projections of SST based on seasonal and monthly time-series of CMIP5 in the literature due to its high uncertainty, this range of mean changes was used as a basis to quantify the associated changes. Likewise, land temperature (based on a 1-in-20-year event) will have an increasing trend between 0.4° and 3.9° where the maximum temperature during summer projected to increase between 0.3° and 3.1°, and minimum temperature in winters also expected to follow an increasing trend by $0.1^\circ - 2.7^\circ$ depending on the projected RCPs. In the same way, the number of days with extremely high temperatures is also expected to increase throughout the 21st century. Moreover, CMIP (Phase 5)-based models project the mean sea level rise of 20 cm up to 59 cm for four RCPs (Walsh et al., 2012).

However, there is no agreement on the future mean annual precipitation anomalies, which is represented by a node namely *rainfall pattern on land,* and anticipated ranges between an increase of 58% to decrease of 40% can be found in the literature (Bureau of Meteorology and CSIRO, 2018). To anticipate the future rainfall pattern and quantify the associated node, annual mean rainfall variation ranges from -23% to $+25\%$ change for all RCPs were used in the quantification procedure. Also, El Nino and La Nina events, as well as tropical cyclones (TCs) and regional storms, are among the most destructive natural events in the region which are expected to continue (Stephens and Ramsay, 2014). Accordingly, the *Storm frequency* node in the BNs network represents natural disasters (including Tropical cyclones and El Nino and La Nina events) that may cause physical damage to coral reefs which was completed according to evidences and studies discussed by Meteorology and CSIRO (2014), Stephens and Ramsay (2014) and Walsh et al. (2012) under different anticipation of sea-level rise and rainfall pattern statuses. In addition, the projected rate of aragonite saturation (associated with ocean acidification) using downscaled CMIP5-based models for the period to 2070 shows a decline from 3.9 ± 0.1 (Ωar) of the early 20th century to the lethal rate of 2.4 ± 0.1 (Ωar) (Australian Bureau of Meteorology and CSIRO, 2014; Veron et al., 2009). Considering the focus of this modelling, aragonite saturation state linked with different RCPs were used to track *ocean acidification*. Therefore, the *ocean acidification* node is directed by aragonite saturation rate and the climate scenario nodes. The associated CPTs were populated based on the downscaled computer-based simulation results reported by Veron et al. (2009), Meteorology and CSIRO (2014), and Frieler et al. (2013).

5.1.2. Land use and cover condition nodes

Geographic Information System (GIS) is generally used for collecting and consolidating multiple spatial data, presenting land conditions graphically as well as analysing and predicting the future spatial patterns of land use and cover conditions (Sahin and Mohamed, 2013). Therefore, *land use pattern* and *land cover condition* nodes were projected by undertaking GIS-based assessments considering prospective land use patterns under different population growth considering the development plans under management strategies. ArcGIS Desktop 8.1 software was employed as the spatial simulation platform to undertake the GIS-based analysis to map the ecosystem of the region. This research employs the methodology and materials from Mackey et al. (2017) and Sahin et al. (2019). The primary references to predict the future land use and pattern condition of the region were Vanuatu's national policy by Haggarty et al. (2013); findings and discussions of Karim and Harrison (2016); and a related case study by Liping et al. (2018). Specifically, the Vanuatu National Land Use Planning and Zoning Policy report by Haggarty et al. (2013) outlines and describes the land use condition, land use legislation and institutional settings, and future land development opportunities of the state of Vanuatu. While, Karim and Harrison (2016) have investigated the climatic, institutional, and cultural factors governing land use patterns in Vanuatu.

Proportions of ecosystem types by area for the whole Island were measured as tropical forests including low height (less than 20 m), medium (more than 20 m) with open and closed canopies (totally around 87%); coastal coral (approximately 7%); grassland (approximately 4%); fresh inland body water and other types (less than 2%). However, these proportions are changing rapidly over time mostly due to the fast expansion of population pressures, predominantly in the east and south-east Tanna (Mackey et al., 2018). The changes of land use and the land cover conditions over time can have considerable impacts on the runoff quality and quantity into Port Resolution, and henceforth, have adverse impacts on the coral reef health condition. Consequently, three states (including conservation, subsistence gardening, transformed non-agroforestry) for the *catchment land use* node and three states (including intact, modified and transformed) were assigned to the *catchment land condition* node. Specifically, the subsistence garden area per capita (i.e. 0.72 ha^{-1} in 2016) was an important indicator to complete the catchment land use CPT. To illustrate an observed example, 80 km^2 were converted to subsistence gardening within five years from 2011 according to the GIS-based analysis mostly because of the rapid population growth. Accordingly, the proportion of the future subsistence gardening area was anticipated in the model based on the median population growth rate under different states of local governance and customary stewardship. However, the land cover change rate cannot continue with the current area per person rate or indicator due to the limited available lands in the Island, which shows the importance of taking other considerations into account. The initial draft of both land use and cover condition CPTs were drafted supported by downscaled GIS-based analysis of Port Resolution area which was confirmed by experts. Fig. 3 demonstrates an overview of Tanna Island's current ecosystem with Port Resolution GIS inset map.

5.1.3. Socioeconomic nodes

Two nodes, namely *population growth* and *governance and customary stewardship*, were added to the DAG representing the primary socio-economic drivers of anthropogenic impacts in a local-scale. According to the UN Revision of World Population Prospects report (United Nations, 2015), the latest Census shows 32,280 as the population of Tanna, and it is projected to peak at 78,788 by 2070 based on the average estimate of 1.4% annual growth rate (Mackey et al., 2017). However, considering the highest and lowest mean estimate rates, the population is projected to be between 50,000 and 85,000 by 2070. Accordingly, the thresholds of low, medium and high states of the *population growth node* were defined as the low state ranges for projections below 65,000 and the high state ranges for projections more than 80,000.

Given the socio-cultural characteristics of SIDS, the impacts of the unique mechanism of local governance and traditional stewardship systems were shown in the model by dedicating a node titled as *governance and customary stewardship*. To finalise its CPT, the benefits of the effective political governance and customary stewardship arrangements and the impacts on the child nodes were considered based on Tanna's current kastom-oriented or socio-cultural processes. For this purpose, Mackey et al. (2017), Karim and Harrison (2016), Forsyth (2009) and Johnson et al. (2018) studies were referenced to formulate an initial depiction of the local governance and customary stewardship systems, which were finalised based on experts' judgment.

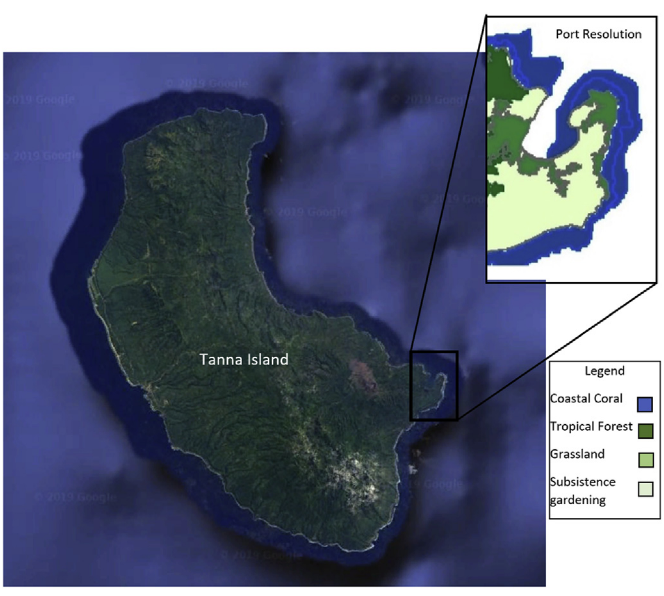

Fig. 3. Tanna Island's map with Port Resolution inset
(Resource: Island Map from Google map and Port Resolution inset from ArcGIS 8.1 software output).

5.1.4. Management intervention for adaptation nodes

The nodes representing management interventions were selected from a portfolio of potential options presented and discussed with experts (see Supplementary File B **for the full list**). The states of the final management nodes were defined to reflect regulatory intervals due to the context of this model. A summary of nominated management options and their mechanism of impact are summarized as follow:

- *Fisheries management* with a focus on control overfishing of endangered or popular species (such as parrotfish in Port Resolution); seasonal restrictions for all commercial fishing (McClanahan et al., 2011); transformation of fishing methods to safe operating space for coral reefs for both subsistence and commercial fisheries (Sadovy and Domeier, 2005); alterations of the coral sea fishing zones by supporting locals with transport and modern fishing facilities (Eriksson et al., 2017). Community marine conservation areas, including through practising kastom seasonal taboos, is an approach used in Vanuatu and other Pacific SIDS as a governance mechanism for fisheries management in coral reef ecosystems.
- *Recreational activities supervision and management* aim at delimiting the recreational activity zones within which coral reefs and other endangered species are reasonably safe with a sustainable management system through effective monitoring and social capital (Godfrey, 2009).
- *Artificial reef structures and fish aggregation devices (FADs)* option has a potential for increased fish abundance (Rendle and Rodwell, 2014), and therefore, for recovering reef sites. Since the reefs in place have low natural structure and with a gentle slope ranging from 1 m deep on reef crest down to around 15 m on the ocean-exposed side of the reefs, the use of artificial benthic structures was selected as a potential solution for the reef site in Port Resolution. Particularly, placement of artificial reefs can cause encouraging new coral growth as a base for coral recovery (Raymundo et al., 2009) as well as protect coral reefs from certain physical damages such as providing a physical deterrent to trawling (Rendle and Rodwell, 2014) and moderating the severity of the medium waves (Silva et al., 2016). This option can also control the potential causative relationship between reduced herbivorous fish abundance with the prevalence of coral diseases.
- *Water quality improvement plans (WQIPs)* focus on improving the quality of water flowing from the catchments and coastal zones

adjacent to the Port Resolution reef site. Specifically, WQIPs should consider all sources of land-based water pollution sources including agricultural, local communities, and tourism activities (Comte and Pendleton, 2018) through assisting and encouraging locals to maintain septic systems and convert cesspools to septic systems and extending discharge points into deeper water, providing guidelines on optimal fertilizer types and application techniques, and promoting installation of adequate and well-managed sewage treatment plants for the future development and tourist resorts (Great Barrier Reef Marine Park, 2014).

- *Coastal land use sustainable development plans* seek to prevent sediment erosion into the bay and coastal waters caused by farmlands' clearing and deforestation; to maintain infiltration rate; to control wastes into the port; to extend discharge points further offshore. Generally, the negative relationship between coral reefs health condition and proximity and density of coastal population (Mackey et al., 2017) should be minimised through effective, sustainable land-use practices (Burke et al., 2011). Therefore, coastal land use management for Port Resolution can lead to healthier water quality adjacent to the reefs by increasing the rate of contaminants' dispersion with greater dilution as well as minimising the human land-based activities in the vicinity of reef sites.

5.2. Pressure layer

5.2.1. Harvesting nodes

Unsupervised and uncontrolled harvesting can lead to irreversible damages not only to the fish stock but other marine ecosystems (Hughes et al., 2015) as reported in many sites in Melanesia, Pacific Ocean Region (Hardy et al., 2013). The latest surveys of the marine biologist experts engaged in this study show the mean fish abundance of around 65 per 200 m^2 ($\pm$25 SE) in the Port Resolution reef site. Therefore, the impacts of both unsustainable subsistence and commercial harvestings were assessed over the given time horizon by taking the assessments and the measurements of other similar regions into account, including: the formulated fishing thresholds by McClanahan et al. (2011); findings and discussions of Dunstan et al. (2017); modelling results of Gilby et al. (2016); and a review of 44 years destructive fisheries behaviour in a reef site reported by Nurdin et al. (2016). Also, according to Brewer et al. (2013), the accessibility of the major local marketplaces of the Island (currently Lenakel in South-west side of Tanna) and the availability to overseas markets was assumed as further drivers impacting on the scale of harvesting. Other considerations, including the availability of fish stocks in other sites around the Island and the suitability of fishing devices and methods, were incorporated based on the experts' judgment.

On the other hand, the *harvesting intensity* node was projected based on the assumed effectiveness and level of local governance and federal policies in place. The extent of all harvesting related impacts was assembled by adding a divorce node namely *total harvesting pressure*. This node was defined as and a function of both harvesting scale and harvesting type or intensity. Thus, the CPT of the harvesting nodes were populated based on the expected population scenario, land use condition and cover conditions, capital work and infrastructure conditions, then scrutinised and approved by the expert panel.

5.2.2. Water quality nodes

Thresholds of the poor and good states of the *water quality* node were adopted from water quality component assessment for coral reefs presented by Fabricius (2005). Populating the CPTs of the *water quality* nodes were undertaken under different population and land condition scenarios considering the formulated water quality index (WQI) for marine ecosystems presented by ISRS (2004); water quality component-based assessment for healthy reef system based on nutrient and sediment loadings by Risk (2014); nutrient-based water quality definition by Bruno et al. (2007); water quality threshold definition by De'ath and Fabricius (2010); and impact assessment of terrestrial runoff quality on coastal coral reefs measured and studied by Fabricius (2005). Particularly, the trajectory of nutrient loading level under different scenarios was predicted by experts referring to nutrient enrichment and eutrophication model presented by D'Angelo and Wiedenmann (2014) in consideration of Port Resolution's specific characteristics. In a similar manner, the joint probability of sediment load level for every combination of sea-level and rainfall conditions under climate change RCPs, and coastal cover condition were calculated by experts based on the findings of Fabricius (2005), Gilby et al. (2016), and Reef-2050 (2017).

5.2.3. Tourism and capital work nodes

The strategic tourism action plan of Vanuatu (VSTAP) (Government of Vanuatu, 2014) explains the tourism carrying capacity of the country, and accordingly, forecasts different short-term scenarios of future tourism growth. To complete the CPT, the prospects of tourist activities at the study area given the impacts of four RCPs (Klint et al., 2012) were assessed based upon: population projections; various capital works implications; infrastructure as suggested by Gössling and Hall (2006). Tourist facilities were projected by experts based on the assumptions detailed by Government of Vanuatu (2014). Similarly, the *capital work*, that is the parent node of the *recreational activit*ies node, was populated by system modellers based on the hypothesis delivered in the national sustainable development plan of Vanuatu (Vanuatu, 2030, 2017), VSTAP (Government of Vanuatu, 2014), and in consideration of the GIS mapping of future land use condition.

5.3. State layer

The state layer of the DPSI framework consisted of three nodes, namely, *coral bleaching*, *coral diseases*, and *physical damage*. These three nodes, as discussed below, have a significant direct bearing on the health and resilience of coral reefs.

5.3.1. Coral bleaching node

For CPT completion, the intervals and thresholds of states of the node were explored based on the discretised class intervals resulting from the multivariate classification of datasets analysed by Krug et al. (2013). Besides, Frieler et al. (2013) projected the fraction of the coral reefs at risk of long-term degradation (%) under different global mean temperature changes based on the thermal tolerance of corals. According to Frieler et al. (2013), even limiting global warming under 1.5° can only preserve around 10% of world corals. While, ocean acidification can reduce thermal tolerance of corals, with having more significant roles in lower warming scenarios or RCPs (Anthony et al., 2011).

The symbiotic relationship between corals and their algal symbionts are being disrupted by climatic stressors causing coral bleaching (Hughes et al., 2017b), and therefore, many researchers are highly sceptical about the coral reefs ability to persevere over a long-term period with severe consequences of climate change. However, despite these scepticism about the resilience of coral reefs under changing climate conditions, Hughes et al. (2018) have recently contended that the ability of coral reefs to change the ongoing trajectory of ecosystems degradation, known as ecological memory, can increase their resilience against the mass bleaching events even under rapid ocean warming. Therefore, the CPT of the *bleaching* node were populated based on the probability table of bleaching event attained by incorporating findings of Frieler et al. (2013), and with the modelling results of Krug et al. (2013) and corroborated by the bleaching event of ten Pacific coral reef sites which have been identified as being identical to the Port Resolution reef site reported by Barkley et al. (2018).

5.3.2. Coral diseases and shift to algal dominance node

As mentioned before, the complexity of CPT learning processes can be managed by using divorcing nodes, such as the *water quality* and the *harvesting pressure* nodes. This divorce node act as an interim node to represent multiple factors or stressors (i.e. nodes). The same modelling strategy was employed to measure the impacts of water quality on the *coral disease* node. So, the impacts of residential and agricultural waste load, nutrient concentration, sedimentation, and the WQIPs on the prospect of coral disease were measured as water quality in combination with other drivers according to discussions of Vega Thurber et al. (2014), the conceptual model of coral bioindicators in response to water quality conditions presented by Cooper et al. (2009), and the formulated relationship between algal growth and coral health by Nugues et al. (2004).

Moreover, the role of ocean acidification and warming in the coral disease were reflected in the CPT based on the relationship function presented and exploited by Anthony et al. (2008) and Bruno et al. (2007). Next, the long-term impacts of harvesting pattern and behaviour on the coral disease were projected based on the discussion of Scott et al. (2015) demonstrating the abundance of fish impacts on reefs. Lastly, the populated CTP was consolidated using the opinion of the multidisciplinary experts.

5.3.3. Physical damage

Research articles with different case studies across the world (including GBR, Hawaiian coral zone, Persian Gulf corals, and corals of the Red Sea and the Gulf of Aqaba) were used for understanding the impacts of recreational activities on coral reefs. A selection of applicable reported case studies were employed in support of the projection and measurement of human-induced physical damage for CPTs completion for the low and high level of tourism activities impacts (Gladstone et al., 2013; Hannak et al., 2011; Kininmonth et al., 2014; Ku'ulei and Cox, 2003; Williamson et al., 2017). Similarly, the recorded damages from natural and climate-related events published by the Secretariat of the Pacific Regional Environment Programme (SPREP) and Johnson and Walsh (2016) were employed to project the extent of physical threats to reef communities under different climate scenarios. As an illustration, according to a post-cyclone survey in early 2015 at 14 reef sites recorded by SPREP (2016a), between 19.5% and 39% of hard coral cover on the surveyed sites north and north-west Efate, state of Vanuatu in the Pacific Ocean were documented to have considerable signs of significant physical damage (Johnson and Welch, 2016).

5.4. Impact layer

The resilience of coral reefs is negatively correlated with the future trend of bleaching, projections of disease and shifting from coral to algal dominance, and the potential climatic and non-climatic physical threats (Burke et al., 2011). A severe condition of each of these three parent nodes can result in catastrophic mortality or irrecoverable loss of coral community. The probability of the different states of this node, also known as the target or impact node within the DPSI framework, is assigned for all the combinations of parent nodes' states accordingly. Hence, CPT *of the health and resilience of coral reefs*' node was populated based on the combination of multiple and individual states of parent nodes.

6. Scenario setting

Once the model quantification was accomplished, scenario settings were defined to conclude the modelling procedure with the last phase. Scenario-based analyses aimed at predicting the health and resilience of coral reefs in response to the management strategies and prospective scenarios covering both direct and indirect anthropogenic as well as climatic disturbances by 2070. Scenario nodes' states were changed to compare the target node of persisting or declining coral reef health and resilience. Evaluating a combination of meaningful and plausible scenarios provided a rational comprehension about the condition of the reef based on the best-case and worst-case combination of states of scenario nodes. A set of management strategies, including business-as-usual (BAU), coupled with different population and governance level scenarios were considered under all four RCPs. This scenario-based modelling is expected to provide decision-makers and stakeholders with a holistic view and insight into the future condition of the Port Resolution reef site as well as a realistic perception of the effectiveness of management strategies. The results can also be exploited in support of environmental planning and decision-making processes.

There were four main scenarios used in the modelling procedure:

I. **Sustainable intervention management scenario** (*Scn.SIM*): This scenario expects that the population is expected to grow with the lowest projected rate (as discussed in Section 3.3.3.1) and with a satisfactory or improved level of governance and customary stewardship due to the continuing strength of traditional practices. All proposed management interventions in this research are assumed to be in the highest possible level of effectiveness including executing strict fishing regulations, effective WQIPs, extended installation of FADs and artificial reefs across the bay, and successful implementation of coastal planning and marine-protected zones. However, this scenario is considered the most expensive combination due to the extensive deployment of WQIPs, FADs as well as the lower expected tourism and fisheries income in both subsistence and commercial scales.

II. **Partial intervention management scenario** (*Scn.PIM*): This scenario projects the federal government control and regulatory efforts are successful in both mitigating the negative impacts of capital works and controlling damaging marine-based recreational activities. Moreover, the ongoing local kastom-oriented or traditional governance and customary stewardship practices are considered as being highly capable of actively supporting management practices. Consequently, coastal land use and marine protected policies are assumed as an effective and successful option over a long-term period. Besides, the local population growth (as discussed in Section 3.3.3.1) is expected to continue growing by the medium estimate rate of 1.4% annually by 2070. In contrast, the potential opportunities provided by costly management options are not being fully employed in this scenario, including ineffective WIQPs, limited use of FADs and artificial reefs, and the modest level of fishing restrictions.

III. **Business-as-usual scenario** (*Scn.BAU*): This scenario assumes that there will be no significant change in management approaches in the face of the changing climate, no fundamental behavioural change in attitudes and priorities of locals, and no effective control over the coastal settlement. In addition, kastom was considered as an effective actor with a sustained role to play in social, political and development processes in this scenario despite its current lesser efficacy and efficiency compared to the past. Therefore, this scenario is kastom-oriented without a significant intervention of additional sustainable management efforts due to the expected effective local governance and customary stewardship. Hence, the factors impacting on the coral reefs' health and resilience are only influenced and controlled through a local self-government system without adopting any further policies, strategies or approaches under this scenario. Lastly, the local population is expected to peak at the highest rate (as discussed in Section 3.3.3.1).

IV. **Unsustainable human interference and management scenario** (*Scn.UIM*): This is the worst-case scenario assuming the lack of effective governmental control and regulatory body in limiting destructive harvesting and managing the adverse impacts of coastal activities, capital works and other damaging recreational activities as well as ineffectual customary stewardship and local governance system. Also, it is expected that the population, specifically settled within the coastal zone, will grow similar to the BAU scenario. Overall, the ongoing local and federal management strategies and policies are assumed to be continuing without any fundamental modification, and all the potential management options, recommended in this research, are ineffective or disregarded.

The settings of the states of the scenario nodes are summarized in Table 1. It should be highlighted that Section 3.3.3 covers considerations related to the nodes and their associated states.

7. Results and discussion

By the completion of the model and the accomplishment of meaningful scenario settings, the health and resilience conditions under each scenario for all four RCPs were projected. Scenario predictions showed the probability of both persisting and declining states. The scenario predictions show the probability of ecosystem condition for the time horizon of 2070. The results of this scenario-based modelling can provide decision-makers and stakeholders with a more holistic view and new insights into the future condition of the Port Resolution reef site as well as a realistic assessment regarding the effectiveness of management strategies. Therefore, the results can be exploited in support of environmental planning and decision-making processes.

7.1. Scenario-based modelling outcomes

Validating predictive models through gauging modelling performance and uncertainty is an essential step before interpreting the model results (Agrahari et al., 2018). Following the model validation (discussed in Section 4.2), the scenario-based analysis was initiated using the four scenarios summarized in Table 1).

Probabilities of declining reef health were considerably lower for *Scn.SIM* compared to the other three scenarios, regardless of climate trajectory (Fig. 4). Probabilities of persistent reef health declined with increasing changes in climate from RCP 2.6 (i.e. persistent reef health probabilities increased from 47 to 74%) to RCP 8.5 (probabilities increased from 15 to 30%). These results provide some understanding of the link between changing climate conditions, as a result of human global scale activities, and the reefs conditions despite the undeniable role of local management interventions. However, even the best climate trajectory (i.e. RCP 2.6) does not necessarily lead to healthy coral reefs in the absence of effective management interventions.

To better understand the direct threats responsible for the coral reefs decline, the predictions on the future conditions of coral bleaching, diseases, and physical damages (under the state layer in the DPSI framework in Fig. 2), are presented in Fig. 5. This colour-coded graph provides a snapshot of the projected future severity of bleaching, diseases and physical damages as well as the degree of effectiveness of different management strategies under the four RCPs. Colours in Fig. 5 also represent the risks associated with each scenario combination and the severe consequences of all listed events (including strong coral bleaching, high level of coral disease and high physical damage to the reef communities). In other words, the higher the probability of listed events, the higher the risks associated with severe consequences for coral reefs.

7.2. Model calibration and validation

Prior to any scenario-based modelling and analysis, the model was calibrated and validated as a matter of course. Due to the specific time-horizon and scope of this research and also inherent uncertainties embedded in ecological behaviour of coral reefs in response to the unknown future socio-economic and climate trajectories, it was infeasible to evaluate the model using the historical data. Therefore, the model was calibrated and validated through and BN-specific evaluation techniques.

Firstly, the model proceeded to the analysis phase through the extensive model development procedure (Fig. 1). The so-called "core model" without the inclusion of management options was developed, analysed and tested before linking the management nodes. Upon the verification of the core model, the management nodes were linked to their child nodes, and the associated CPTs were updated afterwards. The multi-step model development approach resulted in a double model verification process; firstly for the core model, and then, for the entire model.

Following the multi-step model development, the BN model evaluation was conducted. Additionally, validating predictive models (such as BN decision-making models) through gauging modelling performance and uncertainty was an essential step before the exploitation of the modelling results (Agrahari et al., 2018). The metrics of prediction performance and sensitivity analyses deliver reliable measures to evaluate the model performance in BN modelling (Aguilera et al., 2011). BN-specific evaluation methods used in this study consisted of prediction performance (i.e. The robustness test using confusion matrix) and the sensitivity analysis and entropy reduction approach, as detailed in the

Table 1
State settings of the management and scenario-nodes.

Scenario	Title of nodes						
Title	Population	Governance & customary stewardship	Control fishing	Coastal land use	WQIPs	Marine protected policy	Artificial reefs and FADs
Scn.SIM	Low	Effective	Strict	Effective	Effective	Extended	Extended
Scn.PIM	Medium	Effective	Strict	Effective	Ineffective	Extended	Limited
Scn.BAU	High	Effective	Moderate	Ineffective	Ineffective	Limited	None
Scn.UIM	High	Ineffective	None	Ineffective	Ineffective	Limited	None

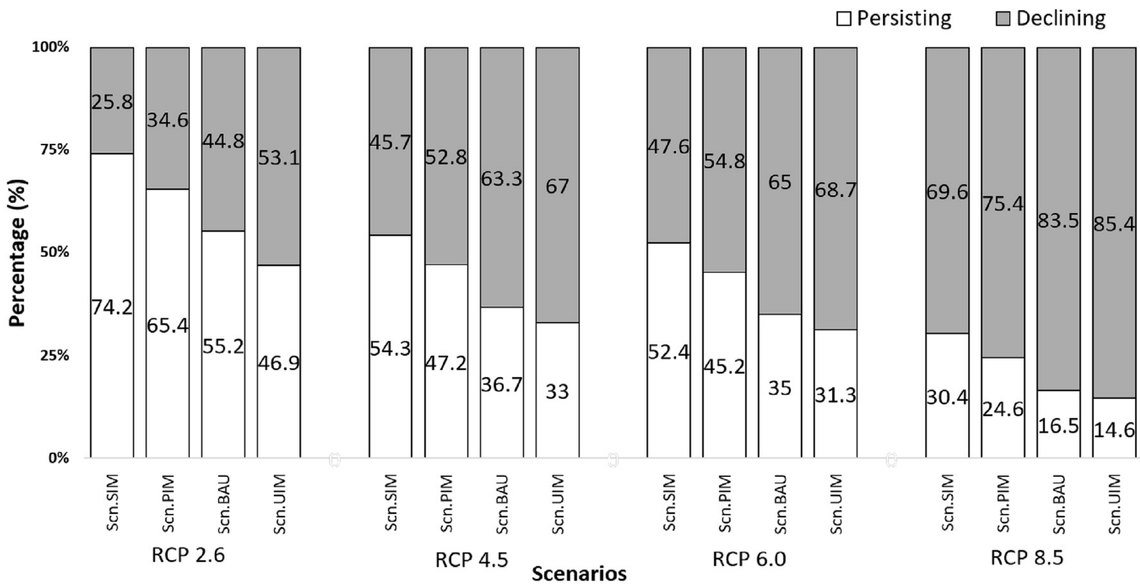

Fig. 4. Probabilities of persisting and declining health and resilience of coral reef from multiple-stressors interactions under different scenarios (the RCP with a number indicates the climate change scenarios and the charterers represent the scenario assumptions as summarized in Table 1).

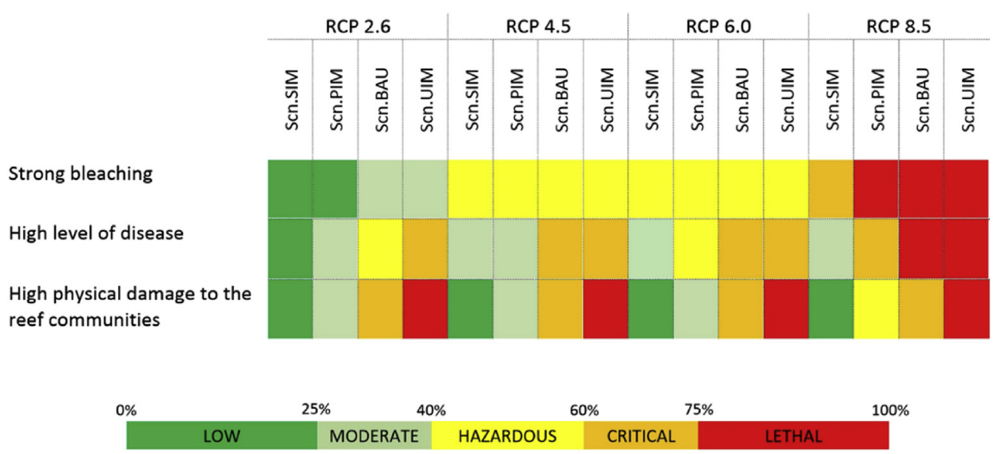

Fig. 5. A colour-coded table of projected conditions of bleaching, disease and physical damage stressors based on different scenario-modelling results (up) and the legend bar (down). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

subsequent section. It should also be mentioned that in addition to the described numerical validation methods, BN logic and modelling has been qualitatively validated through a series of workshops attended by various discipline experts having Tanna experience.

7.2.1. Prediction performance

To undertake prediction performance validation, a data set was generated using an identical BN model for different scenarios replicated in a new software designated for this test, and the results of different combinations of nodes were compared to check the performance of the new model once the net was compiled. For this purpose, A data set with 10,000 records were generated using the *Generate Data* function of the GeNIe software version 2.1.1104.0 (BayesFusion LLC, 2016) The new dataset file comprises of the values of the nodes randomly generated based on the probability distribution associated with the DAG and through the *learning and generate data file* function of GeNIe. Next, the proficiency and robustness of the modelling results in predicting both persisting and declining conditions of the health and resilience of coral reefs were tested using a confusion matrix by supervising the predicted values against the generated outcomes (Table 2).

Also, a receiver operator characteristic (ROC) curve was plotted for persisting and declining conditions of the target nodes using the values of the confusion matrix (Fig. 6). The ROC graph shows the true positive rate (sensitivity) and false-positive rate (1- specificity) over a range of cut-off values at various threshold settings, and accordingly, the area under the ROC curve (AUC) was measured, as a simple numeric indicator of the model predictive performance (Semakula et al., 2016). As a result, the model achieved 84.81% accuracy in predicting the target node's states, or in other words, the mean AUC of 0.848 for both states of the health and resilience of coral reefs which is within the acceptable range of predictive accuracy. The results of predictive accuracy assessments using AUC shows the reliability of the model performance.

7.2.2. Sensitivity analysis

Selecting a suitable sensitivity analysis method for assessing the performance of a BN model should be undertaken mostly based on

Table 2
Confusion matrix for the robustness test.

	Health and resilience of coral reefs (Predicted)			Precision (%) (Accuracy rate)
Health and resilience of coral reefs (Generated)	Condition	Declining	Persisting	Overall
	Declining	2317	829	73.64
	Persisting	690	6164	89.93

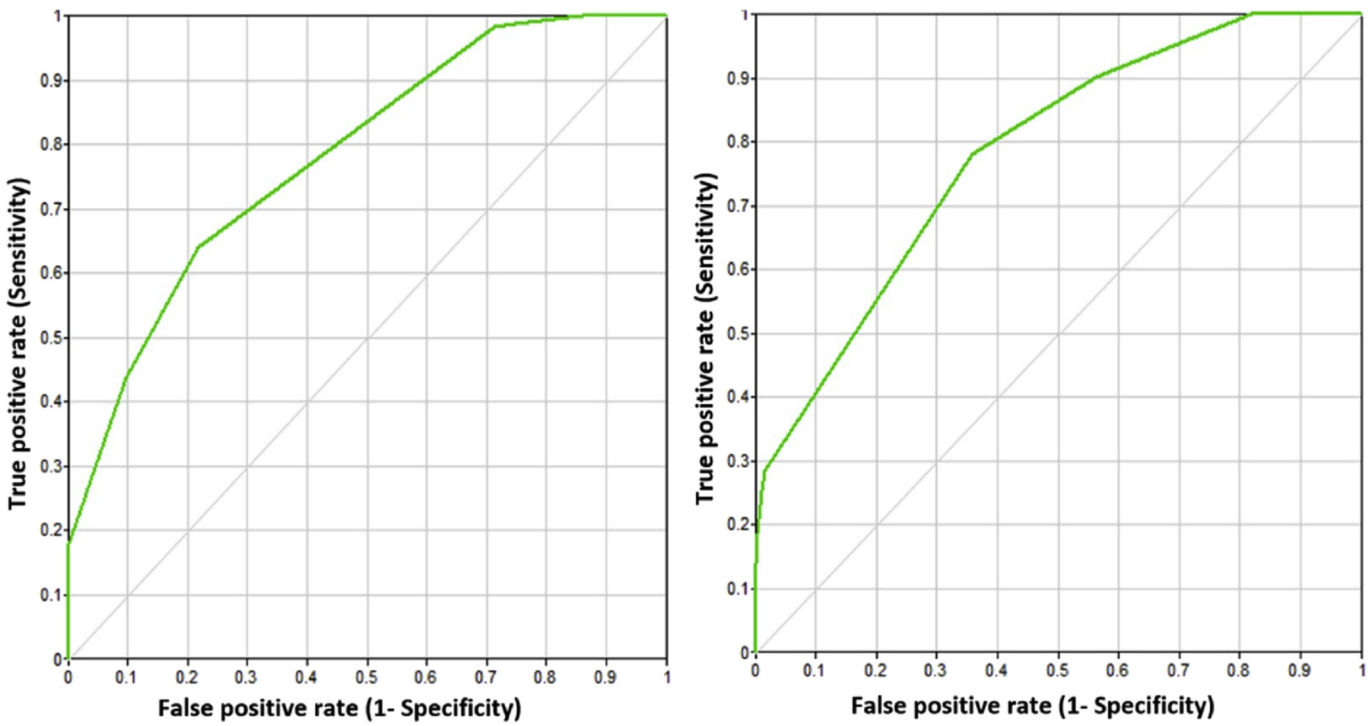

Fig. 6. Receiver-operating characteristic curves for persisting (Left) and declining (Right) states of the target nodes.

the model components and structure (Rositano et al., 2017). Sensitivity to findings method was favoured due to the modelling purpose and the non-linearity of the BN structure. The sensitivity analysis was intended to fulfil two aims: scenario-modelling result assessment and model validation. The analysis for the former purpose was measured by the entropy reduction and the mutual information values using Netica software. To deliver the second aim, the sensitivity analysis was conducted by entering an action or setting a constant value to a random node and changing the conditions of other management and scenario nodes. This action was repeated for some other nodes randomly by system modellers to ensure the model responds reasonably to significant changes.

As another quantitative evaluation method to better capture the modelling outcomes, entropy reduction calculations were conducted to identify the sensitivity of the target node to the parent nodes and other nodes. Entropy or self-information of a selected node in BN modelling is commonly exploited to rank the input variables based on their influence on the selected node as well as to measure the uncertainty or randomness of the selected node characterised by the constructed probability distribution (Semakula et al., 2016). The entropy reduction calculation variables are commonly used to measure sensitivity analysis among the nodes with categorical or discrete states (Rositano et al., 2017). In general, the greater entropy reduction of a node means the higher impact of that particular node on the target node. Hence, sensitivity analysis based on different scenario settings were conducted using the replica models in GeNIe, as a suitable platform, for all four RCPs in which all nodes were modelled with discrete states. The entropy reduction values show the higher impact mass bleaching on the future health and resilience of coral reefs compared to the coral diseases and physical damage under all scenario settings. However, the sensitivity analysis results indicate different scenarios and assumptions can change the degree of the impacts of these three parent nodes on the target nodes. Specifically, bleaching and coral disease have approximately the same degree of impact on the health and resilience of coral reefs under the lowest emission trajectory with Scn.BAU and Scn.UIM scenarios (i.e. RCP 2.6). Fig. 7 demonstrates the reduction percentage values (%) between the target node (the health and resilience of coral reefs) and the parent nodes including coral bleaching, coral diseases, and physical damage to coral communities.

7.3. *Planning and management implications*

The modelling procedure and the results for the different combinations of sustainable management scenarios under RCPs can provide planners and decision-makers with important insights.

- **The modelling approach** used here can be adapted, transferred and applied broadly to other SIDS, and the specific findings are likely relevant elsewhere in the South Pacific context.
- **The listed nodes and potential management options** within the DPSI framework can provide future similar research and planning efforts with useful archive references.

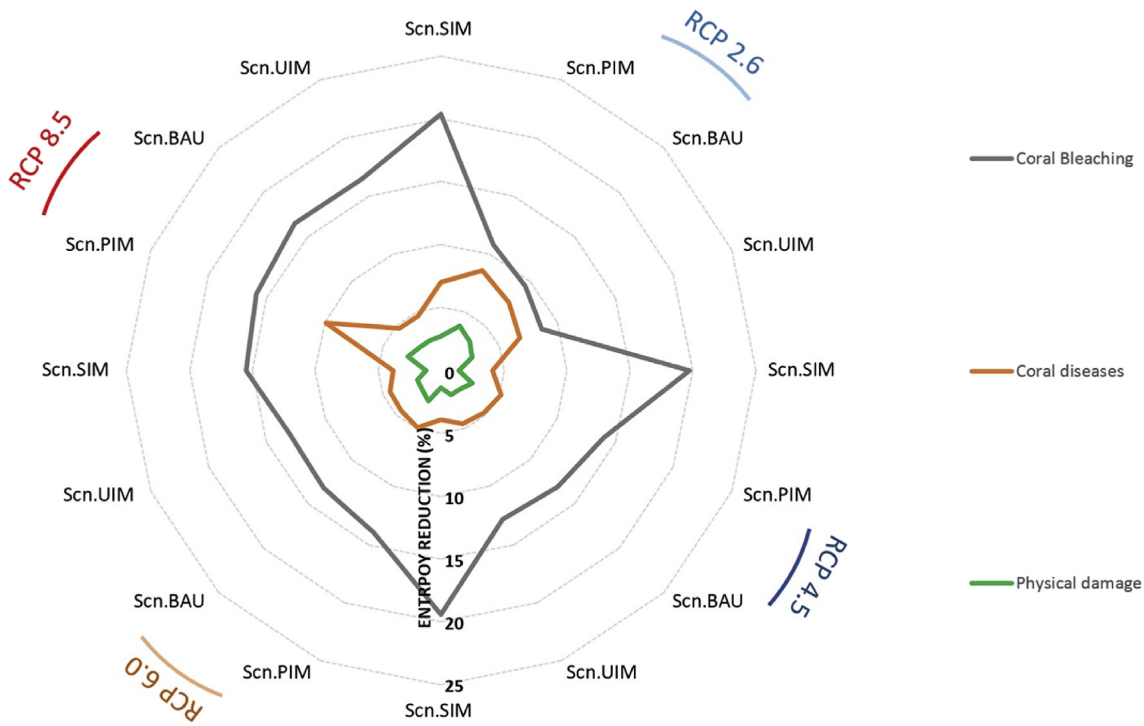

Fig. 7. The values of entropy reduction (%) of the parent nodes of "the health and resilience of coral reefs" node for four scenario settings under four RCPs.

- **The global impacts of climate change** are the main factors affecting the health and resilience of coral reefs and are more important even though there are substantial effects from the non-climatic stressors.
- **The effectiveness** of various combinations of sustainable management strategies was shown to be heavily dependent on the extent of climate change. Management interventions can have a constructive and critical role in promoting reef resilience under the relatively limited climate change impacts associated with low GHG emission by 2070 (i.e. RCP 2.6). On the other hand, these management options are unlikely to adequately protect the coral reefs in the long-term under RCP 8.5 because of the projected mass coral bleaching events.
- **Devastating consequences** of the loss of coral cover would dramatically reduce the flow of the associated ecosystem services. The relatively high but potentially manageable probability of the increasing vulnerability of coral reefs under the impacts arising from RCPs 2.6, 4.5 and 6.0 highlights the importance of the recommended adaptation strategies options.
- **Coupling Kastom-oriented solutions** such as seasonal taboos on fishing with cost-effective sustainable management schemes can mitigate the adverse climatic and non-climatic pressure on coral reefs. Specifically, the evaluation of Scn.BAU and Scn.PIM scenarios demonstrate that adopting such a coupled approach is more likely to yield better adaptation outcomes over the long term. This approach may be preferred over a short-term period than poorly implemented high-level government strategies due to the limited institutional capacity and financial resources available to SIDS and their outer islands, in particular, limited infrastructure, low per capita income and poor access to latest technologies and facilities.
- **In the absence of effective sustainable land-use practices**, the high population growth rate is projected to significantly exacerbate the destruction of coral covers as evidenced by the results of sensitivity to population growth node analysis, and scenario modelling (i.e. Scn.PIM and Scn.BAU).
- **Under the RCP 8.5,** coral reefs of SIDS are very likely to suffer the same irreversible decline from bleaching as reefs globally (Frieler et al., 2013), and local-based management interventions have a lesser effect on reef health compared to the other RCPs due to the severe climatic and environmental impacts. This conclusion supports the necessity of adopting additional policies to substitute the lost ecosystem services provided by coral reefs, in addition, to implement the highest level of management interventions, in any future decision-making processes if the future global emissions track RCP 8.5.
- **Comparing the results of this study** with other coral reef BN-based assessments confirms the need for scenario-based modelling under integrated local and climatic stressors. For instance, although this study proves that different management policies are to be adopted under different climate change trajectories, Ban et al. (2014) identified the overshadowing role of climatic changes on reef communities in general. For another example, Gilby et al. (2016) determined that the marine reserves and sedimentation control strategies were the most effective management options for protecting coral reefs; the herein study further built on this finding by proposing scenario-specific options that mitigate the harms of different development pathways.

In summary, the probabilistic projections of the risks of declining reefs condition under different scenario-based assumptions indicate that preserving sustainable coral reefs ecosystem management in the long-term perspective requires the implementation of further actions and policies in Port Resolution. Adopting an integrated community-based sustainable and management approach towards reducing the vulnerability of the studied reef site is a strategy that warrants the better effectiveness of planning strategies.

8. Conclusion

This study explored the long-term perspective of the future health and resilience condition of coral reefs under different combinations of management strategies and under four climate change RCPs. A BN model was developed through a systematic approach by following a stepwise modelling procedure. Subsequently, twelve scenario settings were defined based on the effectiveness or the extent of management strategies, climate change trajectories, and future population projections. The presented probabilistic scenario modelling results can provide researchers and decision-makers with a more holistic understanding of the long-term impacts of climatic and non-climatic stressors and the effectiveness of management interventions on coral reef condition. Also, the conceptualisation phase can provide further insight into the causal relationship between these multiple stressors and interventions.

The modelling procedure and DPSI framework presented here, along with the hybrid systems approach, can be used as the basis for further model development for investigating marine ecosystem impact assessment and decision-making processes. Environmental assessment and planning are a process rather than an outcome which benefits from an integrated approach (Kelly et al., 2013). According to Hamilton et al. (2015), a holistic environmental assessment and modelling require the consideration of different aspects and dimensions of integration within multiple layers that relate to the systems and methodological requirements as well as other key drivers of the applied integrated approach. Hafezi et al. (2018) introduced the concept of a multi-layered planning approach that provides information that can inform more holistic climate change adaptation plans for SIDS. The modelling approach used in this study draw upon this multi-layered approach by (1) employing participation-based, probabilistic and spatial tools (i.e. BN and GIS-based) and process simulation modelling; (2) including social, climatic and ecological factors; and (3) considering a range of structural, social including community-based, regulatory, and ecosystem-based approaches in the selection and inclusion of the sustainable management interventions and adaptative strategies. Further development of the novel modelling procedure presented in this study within a decision-making framework will support improved adaptation planning.

A reliable and accurate modelling of coral reef condition requires the consideration and formulation of the dynamic and temporal interrelationships of key stressors and accumulative impacts. However, this task is compounded by (i) the low level of biophysical and socio-economic data usually available in developing country SIDS to parameterise models and (ii) the complexity of the reefs system and their responses to the anthropogenic and climatic stressors. The BN modelling approach, which is based on the acyclic and hierarchical relationships of variables, is an effective way of exploring and comparing the effectiveness and sustainability of different management strategies. While the current BN model incorporates many of the significant variables, it has some limitations. Decision-making processes for selection of adaptation strategies for implementation should incorporate additional socio-economic analyses such as cost-effective analysis and social acceptance. Further research is also needed into how the quantity and quality of the various eco-system services vary with coral reef condition.

This study provides further evidence that the BN technique is a practical and useful modelling approach for understanding ecosystems, coral reefs in particular. Employing BN through the presented stepwise modelling procedure is more likely to yield better modelling outcome over the long-term where there is a high level of uncertainty in modelling key processes and variables including in the face of uncertain future climate conditions and human activities. In addition to documenting the application of the BN modelling approach to adaptation problems in SIDS over a long (~50 year) time horizon, this study has further the existing reef management BN models through a hybrid systems approach inclusive of coupled DPSI and structural analysis BN-based probabilistic scenario modelling. The results predict the risks to the health and resilience of the Port Resolution coral reef system to the adverse impacts of climate change and harmful human activities and the possible success of adaptations strategies. A sobering conclusion was that despite the current satisfactory condition of coral reefs in the case study zone, their health and resilience would be threatened severely by 2070 in the absence of implementing adaptation strategies and associated sustainable management interventions.

CRediT author statement

Mehdi Hafezi: Conceptualization, Literature review, Data curation, Methodology, Software, Writing- Original draft preparation.
Oz Sahin: Data curation, Methodology, Investigation, Writing-Original draft preparation, Reviewing and Editing.
Rodney A. Stewart: Methodology,Validation, Writing- Original draft preparation, Reviewing and Editing.
Rod M. Connolly: Data curation, Validation, Reviewing and Editing.
Brendan Mackey: Reviewing, Editing and Supervision.
Daniel Ware: Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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