Assessing how ecosystem-based adaptations to climate change influence community wellbeing: A Vanuatu case study

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Abstract

Climate change poses significant threats to wellbeing and livelihoods of people and the ecosystems in many Small Island Developing States (SIDS). Adaptation solutions must counteract these threats while also supporting development in vulnerable SIDS. Suitable options need to ensure that connections between the social, economic and environmental dimensions of socio-economic systems are defined in a way that can support how decisions are made (and by whom) and how these can impact on other parts of these systems. This is particularly important in many Pacific SIDS, where communities practice customary natural resource management and continue to rely on local natural resources. In this study, we model the anticipated impacts of climate change and the benefits of the ecosystem-based adaptation (EbA) approaches on community wellbeing in Vanuatu. To do this, we applied participatory and expert elicitation methods to develop a Bayesian Network model, which was designed to evaluate community wellbeing responses at four explicit spatial scales. The model includes both acute and chronic impacts of climate change, the impact of coral bleaching and the potential loss of Vanuatu's fringing coral reefs. The model predicts that all proposed EbA interventions will have a positive impact on wellbeing in all four locations to some degree,

by either directly improving the integrity of Vanuatu's ecosystems, or by protecting these ecosystems as a positive spill-over of related actions. Significantly, it also predicts that if climate change exceeds 1.5 oC of warming, the costs of achieving the same level of wellbeing are increased.

Keywords: Participatory Bayesian Networks; Adaptation planning; Small Island Developing States; Adaptation cost and benefit

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Introduction

Climate change represents the greatest ongoing threat to the lives and livelihoods of people in Small Island Developing States (SIDS) (Gheuens et al., 2019; Klock and Nunn, 2019; Thomas et al., 2020). Beyond the impacts of extreme events like droughts, floods and cyclones, incremental changes in climate will reduce the reliability of rainfall and create uncertainty for communities that rely on natural resources and predictable weather patterns for their food and water (Gheuens et al., 2019).

Many adaptation activities are project-based and involve cost-benefit analysis of alternative interventions, such as capital works or nature-based solutions (Mackey and Ware 2018). However, more comprehensive approaches are needed to identify and implement adaptation pathways for climate-resilient development in vulnerable SIDS (Butler et al., 2016). In these contexts, it is critical to understand the climate vulnerability of communities in a systematic and holistic way (Filho et al., 2020). One approach is to identify appropriate pathways to characterise adaptation challenges via a socio-ecological system (SES), where key environmental, social, cultural and economic dimensions are identified and connected (Cote and Nightingale, 2012). This approach is particularly relevant for Pacific SIDS, where the connection between social and ecological systems (SES) is highlighted by community practice of customary natural resource management and continued reliance on natural resources. These customary practices are built upon a foundation of manipulating or supporting ecological processes (McMillen et al., 2014; Thaman et al., 1993).

Furthermore, the activities of humans have consequences for those species and ecosystems they rely upon, establishing feedbacks between the dimensions. In addition to understanding natural resources, ecosystem service flows and their management, climate change adaptation (CCA) studies require that connections between the social, economic and environmental dimensions of an SES are defined in a way that allows exploration of how and by whom decisions are made, alongside how these decisions impact other parts of the SES (Cote and Nightingale, 2012). In many SIDS, the cultural, or kastom[1], relationships between human and environmental components of the SES are of critical importance in terms of protecting culture, sustaining communities and achieving conservation and sustainable extraction goals (Poe et al., 2014). A context-specific SES therefore represents an approach that incorporates ecological understanding with cultural dimensions of resource use and management, while also incorporating more contemporary western views of governance.

Systems approaches also enable the identification of barriers or constraints to development and intervention points where adaptation options might be useful (Buckwell et al., 2019). As noted by Rounsevell et al. (2012), encapsulating the complexity of human-environmental interactions and scaling up SES models remains an ongoing challenge that requires substantial contextual awareness that can accommodate institutional and policy differences across scales. This is particularly relevant in the case of Vanuatu, where a hybrid system of governance has developed (Farran and Corrin, 2017; Forsyth, 2009). Specifically, formal institutions of representative democracy and the administrative state work alongside traditional customary governance (the Malvatu Mauri, or National Council of Chiefs, which advises on issues of culture and language), which is recognised in the constitution, and practised through village-level decision-making at the Nakamal, the traditional meeting place.

For Pacific SIDS with tight coupling between ecosystems and communities, there is merit in an ecosystem-based approach to CCA that harnesses the capacity of nature to buffer human communities against the

[1] Pronounced 'custom' and loosely translating as such, though the term encompasses broader concepts associated with culture, taboos and natural resource management.

adverse impacts of climate change through sustainable delivery of ecosystems services (Munang et al., 2013). Unlike hard engineering solutions, which can damage, impair and/or block flows of ecosystem services (Morris et al., 2018), ecosystem-based approaches to CCA are designed to minimise impacts and improve the flows of resources from environments that support local people (Nalau et al., 2018a). This aligns with the concept of nature-based solutions (Faivre et al., 2017; Keesstra et al., 2018; Nesshöver et al., 2017) and efforts to harmonise development and conservation targets through the maintenance of ecosystem service flows (Cote and Nightingale, 2012).

Vanuatu case

Our case study locations for the BN are in the Republic of Vanuatu – an archipelago with a dispersed population in the southwestern Pacific Ocean. In total, Vanuatu has a land area of 1.22 million hectares (Fig_Sup 1). Vanuatu's islands are mostly steep, with fertile, but unstable, soils of volcanic origin with little permanent surface freshwater. Shorelines are mostly rocky, with some fringing coral reefs.

The population is estimated to be 272,459, with an annual growth rate of around 2.3% (double the global mean) and a relatively young median age of 20 years (UN-DESA, 2017; VNSO, 2016). In terms of GDP per capita, Vanuatu is ranked 126th from 192 listed countries by the UN (UNSD, 2017). Vanuatu has a history of European colonial interference dating back to the 1880s – one that has included transport of indentured labour to Australia (Hunt, 2007), a base for war operations, and the imposition of tax haven status in service of colonial currency manipulation interests (Rawlings, 2005), all of which have an enduring legacy on the country's political institutions, religious life, society, and economy. Historic colonial and contemporary development of export-based agricultural industries, such as beef, copra, and sandalwood, has also disrupted subsistence livelihoods.

We applied our BN models to four case studies within Vanuatu: at a national scale, for Vanuatu as a whole, at an island scale, using the example of Tanna, for Vanuatu's capital, Port Vila (the only significant urban area), and at the scale of a small community (a series of hamlets) in Port Resolution, on Tanna. These locations and scales were selected to test the efficacy of EbA to deliver wellbeing benefits at different scales, but also in different contexts, particularly when comparing an urban community (Port Vila) with the otherwise predominantly rural society of Vanuatu. As noted by Westoby et al. (2020), exploration of locally-led and co-designed adaptation alternatives across multiple scales enables a useful lens through which analyses of adaptation success and pathways can be conducted.

At a *national* level, broader economic opportunities and employment specialisation are limited. Although the Ni-Vanuatu (the Indigenous people of Vanuatu) face persistent poverty in terms of income and risk indices, linked to increasing environmental and resource pressures, the rural Ni-Vanuatu remain relatively immune from poverty in terms of destitution and food insecurity (ADP, 2007), due to continuation of widespread subsistence gardening and fishing, and access to customarily owned land (Gerbeaux et al., 2007). Furthermore, remittances are sent by relatives who take-up employment in Port Vila or overseas.

However, common to many Pacific islands, customary practices, both social- and resource management-based, are being eroded under the influence of contemporary market-based economics and associated values and practices, such as monetary exchange, economic specialisation, and individualised expression of self (Brosi et al., 2007; Nalau et al., 2018b).

The subsistence food production system across Vanuatu typically comprise a shifting cultivation system, with perennial plantation and a forest arboricultural system (Blanco et al., 2013; Thaman et al., 1993). The productivity of this system and the integrity of the adjoining tropical forests are at the centre of a complex web of interdependencies that impact overall community wellbeing and resilience to climate change (Barnett, 2001; Barnett, 2011). This productivity is under threat, mostly likely from shortened fallow times in the shifting cultivation system (Mackey et al., 2017). As with the land, inshore marine areas are subject to customary ownership and access and are economically and culturally important to the Port Resolution community and coastal communities elsewhere in Vanuatu (Hickey, 2008).

Port Vila is the administrative and political capital of Vanuatu, on Efate island. It is a modernising and fast-growing city (2.24% per year) of around 51,000 people (in the local area council). 64% of the eligible population is employed in some paid work and goods and services are exchanged in a cash-based economy. 74% of households remain involved in some form of domestic food production, but only around 28% engage in any cash cropping. Vanuatu is a tax haven, so economic activity is boosted by the finance sector (Rawlings, 2019).

Tanna is an island in the southern province of Tafea. It is often referred to as the stronghold of Kastom – a place where people still know and revere traditional songs, can trace their lineage, and organise and participate in rituals, community decision-making processes and ceremonies. As Clarke et al. (2019) noted, Tanna represents an island where traditional knowledge can, and must, be embedded into all aspects of decision making, particularly with respect to evaluating the nuanced likelihood of success across a range of climate adaptation alternatives. Tanna is commonly regarded as an example of a community where kastom and modernity coexist (Lindstrom, 2011). Virtually all households are engaged in some food production, with around 80% involved in cash-cropping. Paid employment is limited to 12%, generally in the administrative capital and the few tourism enterprises. Also important in the context of Tanna is the experience of Tropical Cyclone Pam, a category 5 cyclone that passed over the island in 2015 and severely affected communities. An estimated 75% of the buildings on Tanna were damaged by high winds and storm surge inundation (Nishijima et al., 2015). Additionally, the high winds damaged crops and forests, and coral reefs were acutely perturbed. Although the shared memories of the socio-economic and physical impacts of Pam are fading, it remains salient to contemporary decision making.

Port Resolution is a series of small hamlets in the south-east of Tanna. The community depends almost exclusively on a combination of subsistence farming, animal husbandry, and artisanal fishing for sustenance and non-food product harvesting for building dwellings. Marine habitats in the Port Resolution area include significant areas of shallow coral gardens and seagrass beds in some of the more sheltered areas on the lee-side of the reefs. There are no permanent freshwater streams in Port Resolution. The village's water comes from either groundwater wells or from a single pipeline, which runs a significant distance (~10km) from a stream in a nearby mountain range.

Summary of EbA interventions

The specific context for this paper is the Pacific nation of Vanuatu. Earlier work by Buckwell et al. (2019) on Tanna island, in southern Vanuatu, developed and assessed interlinked ecosystem-based adaptations (EbA) projects to address identified risks to the resilience and adaptive capacity of village communities. A cost-benefit analysis and detailed description of the intervention programme can be found in Buckwell et al. (2019). Briefly, the focus of these interventions was to build resilience and capacity in the communities of Tanna by protecting, maintaining and enhancing key ecosystem service flows that support community livelihoods (Mackey et al., 2017). Further to the work of Clarke et al. (2019) and as noted by Buggy and McNamara (2016), the attention was on community-level outcomes, with strong attention paid to exploring inequity that may stem from interventions. This required a detailed and in depth analysis of community and government stakeholders, with work conducted by the project team between 2015-2020 ensuring that an understanding of community structure and functioning and system governance was informed through both formal and informal conversations with Government (at National, Provincial and Area Council levels), Council of Chief representatives, community Nakamal discussions and gender separated focus group conversations with men and women in local communities. Much of this work has formed the basis of the publications of Buckwell et al. (2019) and, as highlighted by Granderson (2017) , work of this type is critical in unpacking gendered perceptions and values associated with both Kastom and developing cash economies and how they might interact with the EbA interventions at the various scales considered in this study. In the current study, to achieve community-level outcomes, two interlinked projects were proposed as EbA, which could be implemented either in coordination with each other, or as stand-alone projects. The two projects, which serve as the basis for developing scenarios at four spatial scales in the current paper, are:

1. Improving subsistence gardening productivity and nursery construction and community radio services. The project anticipates demonstration garden plots and extension officers to drive innovation in subsistence gardening, supported by an upgrade of the regional government's plant nursery. The project would be supported by a community radio station. This project seeks to build capacity and resilience around food production on Tanna,
2. Establishment of a series of community-based conservation areas (marine and forest) to formalize and support reef and tropical forest conservation efforts. In addition to establishing formally recognized conservation areas, this project would support local communities through a community ranger program.

The first project aims to reduce unsustainable harvesting of marine ecosystems and deforestation by improving food security and the second provides a formal mechanism for the conservation of ecosystems. Reducing anthropogenic pressures can enhance the ecological resilience and adaptive capacity of ecosystems in the face of climate change and can maintain the flow of ecosystem services that help local communities mitigate the risks from climate-related hazards (Fidelman et al., 2013).

Subsistence gardens program

To estimate costs for the subsistence gardens program, Buckwell et al. (2019) costed a series of demonstration garden plots, each supported by a salaried local extension officer, with a budget for equipment, a vehicle and botanical needs, a salaried coordination manager, with a budget for an office, equipment and a vehicle, and a community radio station, including programme creation consultancies and equipment, broadcast technology and programming support, to drive engagement with the programme. To assist in the propagation of new plant stock, a centralized nursery is planned. The intervention also incorporated an expansion of poultry stock to increase the protein production capabilities to help manage pests and to increase nitrogen cycling (Dumas et al., 2016). The allocated budgets also included costs for specialist consultancies.

Community conservation areas

Increasing deforestation and declining reef fish stocks represent significant threats to the food security of the people of Vanuatu (Fleming, 2007; Mackey et al., 2017). One approach to safeguard natural resources and improve livelihoods is the establishment of Community Conservation Areas (CCA). CCAs are adaptable and may be of any size, can be privately-, community- or cooperatively-owned and managed, and can support local practices by allowing for the sustainable harvesting of resources, such as fish and non-timber forest products. The CCA interventions proposed by Buckwell et al. (2019) aimed to increase Tanna's formal natural resource management capacity in ways that are based upon, and reinforced by, kastom practices and Vanuatu legislation.

For Tanna, CCAs can include preservation for direct use of both coral reef and tropical forest ecosystems. Both are critical in terms of supplying food and buffering the impacts of climate change (Buckwell et al., 2020). In terms of costings, the proposal includes the establishment of a series of marine and terrestrial CCAs, coupled with a community ranger program, which will provide for a network of local community rangers as implementation managers for each CCA. The rangers will be provided with a wage, resources, responsibilities, training and mentoring. Numerous local benefits can flow from community ranger programmes, including generating local, culturally meaningful, employment (which can encourage younger people to stay on-country on Tanna), building community capacity, and serving as a mechanism for applying traditional knowledge to land and sea management (Moritz et al., 2013).

Combined EbA interventions

Conceptually, interventions that combine the subsistence garden program and the community conservation areas are likely to deliver the synergistic benefits to communities in Vanuatu, through improved food security, livelihoods and conservation of valuable ecosystems and their ecosystem services.

Scale and scope of the study

In this study, we sought to model the anticipated impacts of climate change and the benefits of the aforementioned EbA approaches on community wellbeing in Vanuatu, a Melanesian country that is highly vulnerable to climate risks (Nurse, 2014). Here, we define community wellbeing as follows: "... the combination of social, economic, environmental, cultural, and political conditions identified by individuals and their communities as essential for them to flourish and fulfil their potential" (Wiseman and Brasher, 2008). In addition to universal measures of wellbeing represented by the Sustainable Development Goals (UN, 2015), research on Tanna has revealed that EbA will likely resonate with the community if they support customary natural resource knowledge and management, provide opportunities for generating income, and promote gender equity in decision-making (Buckwell et al. 2020).

Buckwell et al. (2019) evaluated these interventions based on their costs and benefits. Here we explore their impacts on community wellbeing as modelled through a SES. To do this, we applied participatory and expert elicitation methods to develop a Bayesian Network (BN) systems model of the Vanuatu SES. This approach was selected because developing models for integrating multidisciplinary knowledge is challenging and poses varying degrees of complexity, particularly where knowledge is poorly shared or incomplete. A BN approach offers a powerful platform to address these challenges (Clark et al., 2001; Borsuk et al., 2004). An additional benefit of this approach was that it enabled us to explore the degree to which EbA and their benefits could be combined – subsistence garden program plus community conservation areas – and scaled-up and applied to new areas throughout Vanuatu. Therefore, the BN model was designed to evaluate community wellbeing responses at four explicit spatial scales, namely: (1) the village community of Port Resolution in Tanna Island; (2) the whole of Tanna Island; (3) Port Vila (Vanuatu's national capital); and (4) the whole of Vanuatu.

This paper adds value to our several previous papers about these case studies by demonstrating the potential usefulness of Bayesian analysis, a mathematical tool not yet widely used for this purpose, in analysing costs and benefits of overlapping and interacting possible climate change adaptation measures (Sahin et al., 2019; Hafezi et al., 2020a; Hafezi et al., 2020b; Hafezi et al., 2021). This paper does not purport to be an analysis of all risks threatening the livelihoods and human security of the case study communities. In particular, we do not consider here the risks arising from Vanuatu's position on the Pacific "ring of fire", which are manifest in the active volcano on the island of Tanna and in the substantial tectonic shifts at Port Resolution recorded in historical times (Méheux, K. and Parker, E., 2006; Peltier et al., 2012).

Materials and methods

BN is an interactive graphical modelling technique that enables a visual and explicit representation of key factors and causal pathways in a complex system, explicit documentation of key assumptions regarding functional relationships, and testing of hypotheses about system responses. BNs comprise three elements: (1) A set of variables representing a system with a set of states; (2) links from cause to effect showing causal relationships between these variables; and (3) conditional probability tables describing the strength of relationships between these variables (Cain, 2001). BNs graphically represent knowledge about a given system and calculate causal dependencies between parts of that system through probabilities (Pearl, 1986). Their graphical nature enables them to be understood by non-technical users (Chen and Pollino, 2012).

BNs represent a way of applying Bayes' theorem to provide a method of defining a probabilistic model for a complex problem to determine probabilities from cause to effect (forward propagation) and from effect to cause (backward propagation), while explicitly accounting for and representing uncertainty in these relationships (Jensen and Nielsen, 2007; Chen and Pollino, 2012). This use of probability for quantifying uncertainty in reasonings is a fundamental feature of the BN method. Importantly, BNs are particularly useful for capturing the probability of events under a range of complex scenarios, conducting predictive as well as diagnostic analyses, and performing sensitivity and trade-off analyses to determine the best leverage points within systems for reducing risk (Landuyt et al., 2013).

Advantages of using BNs in SES research include the ability to: predict the relations between management interventions and ecosystem responses (Clark et al., 2001; Borsuk et al., 2004); combine variables from different domains, such as social, economic, and climate variables; utilise different types of data, including expert opinion, data derived from models, and observed data (Forio et al., 2015). The capability of using multiple sources of information makes BNs attractive for environmental modelling (Pollino et al., 2007; Forio et al., 2015). BNs can facilitate easy scenario analysis and can rapidly include new information when available. As such, BNs offer a convenient means to visualize the structure of the model of a system, depict the relationships between system variables, and perform complex probability calculations for scenarios given the available evidence. However, BNs also have certain limitations when modelling complex systems. Major limitations of BNs include the inability to incorporate feedback loops and the limited ability of using continuous system variables (Uusitalo, 2007).

BN modelling is increasingly being used in SES research including in: land use decisions (Nascimento et al., 2020); environmental flow requirements (Xue et al., 2016); risk assessment for managers of reservoirs (Bertone et al., 2016); assessing climate change impacts on the whale watching industry (Meynecke et al., 2017); vulnerability assessment of a coastal freshwater systems under climate change (Phan et al., 2018); assessment and valuation of the delivery of ecosystem services (McVittie et al., 2015); and modelling cultural services (Shaw et al., 2016), maritime spatial planning (Furlan et al., 2020) and sea-level rise induced coastal erosion (Sahin et al., 2019).

Bayesian Network (BN) model development

The BN model development procedure used in this study was adapted from Cain (2001) and Jakeman et al. (2006) and consisted of seven steps (Table_Sup 1). Expert stakeholders were crucial to all stages, including defining the scope of the system and identifying the key variables and assumptions that affect community wellbeing. In addition, and throughout the entire research process, engagement with local stakeholders helped the project team to evaluate and appropriately account for local system understanding, including connectedness of resources and, in particular, the ways in which Kastom, health, wealth and education served to modify community wellbeing across scales. The final, seventh step, involved running the model under a range of scenarios to test and compare the influence of different combinations of EbA on the target node, in this case, community wellbeing.

Problem scoping and model development

A BN model consists of qualitative and quantitative components. The qualitative part includes system variables and an influence diagram (which, in the modelling literature, is known as a "directed acyclic graph" or DAG) depicting causal relationships among these variables, while the quantitative part describes conditional probabilities that quantify the strength of the causal relationships between the system variables (Cain, 2001).

Our BN model was developed through a series of participatory workshops with local stakeholders and relevant experts conducted between May 2016 and May 2020 (Table_Sup 1). As mentioned above, informal and formal conversations and meetings with in-country representatives helped to ensure that node relationships and probabilities were determined through consensus. The term 'expert' here refers to a person who has specialised knowledge of a specific field gained through informal learning, academic research or practical experience, including the lived experience of in-country peoples. Contributing experts and, particularly, the authors have considerable knowledge of the case study areas through ongoing research commitments, data collection for related research and engagement with the Vanuatu National Government, the Tafea Provincial Government, NGOs, IGOs and Vanuatu academic institutions. Given the scarcity of primary data and the complexity of the modelled interconnected relationships, the involvement of experts from all relevant fields was key to the development of our BN. Experts helped to better understand issues, identify the relevant data to feed into the BN, assess the uncertainties (data/knowledge), evaluate model performance, and evaluate the modelling output (Petts, 2004). For building, evaluating and running the model, two BN software packages – Netica (Norsys, 2018) and GeNIe (BayesFusion, 2020) – were used to exploit the unique capabilities of both packages.

As an initial step before building the BN model we established the system boundary and identified key variables (Table_Sup 4). The identified variables were then arranged into an influence diagram (Fig_Sup 2) to illustrate the impact of interactions among these factors on the target variable (community wellbeing). The arrows show the direction of the cause-effect relationships among the variables.

As illustrated in Fig_Sup 2, the influence diagram represents the conceptual model of the SES. It contains 27 variables arranged into seven groups, representing: target node (light green); key interventions factors (orange); implementation factors (blue); ecosystem stocks (bright green); exogenous factors (grey); ecosystem-based intervention options (pink); and spatial locations (yellow). The arrows represent the hypothesised causal relationships between nodes which can comprise parent nodes or child nodes (i.e. parent nodes influence one or more child nodes). These dependencies are highlighted in an adjacency matrix (Fig 1) (Dwyer, 2016). For example, the *Education* node has two parent nodes (*Participation* and *Education Facilities*), and three child nodes (*Community wellbeing*, *Health* and *Western Medicine Acceptance*).

Fig 1 BN adjacency matrix showing the dependencies between parent and child nodes in the influence diagram illustrated in Fig_Sup 2

Model Parameterisation

In a BN model, relationships between nodes in the influence diagram (Fig_Sup 2) are quantified through the use of conditional probability tables (CPTs). Due to the limited availability of empirical data, the CPTs were parameterized using experts' judgement in conjunction with information collected through fieldwork activities and sourced from the available literature. To populate the CPTs consistently, as described by Cain

(2001), the best-case and worst-case scenarios were identified and used as benchmarks for allocating probabilities for the other scenarios between the worst and best. CPTs were populated using the location-specific information/data to reflect the characteristics of these locations in the model. Due to the structure of our BN model, the higher the number of parent nodes related to a CPT, the larger that CPT. Thus, populating CPTs is time-consuming. To reduce the number of permutations of a CPT for a node with multiple parents, a 'node divorcing' technique was utilized. The technique involves removing some of the parents of a node by introducing an interim node to the BN and making it a child of the divorced parents and a parent of the original child (Krieg, 2001). For example, the size of the Cash-income CPT was reduced from 512 permutations of seven parents' states to 64 permutations. Then, by using the 'node absorption method', the interim nodes were removed from the final BN. In probability theory, this is called 'summing out a variable', which allows the full joint probability distribution of the variables of the BN to remain unchanged (Norsys, 2018).

Model evaluation

The model evaluation step involves checking the consistency of the BN model, conducting sensitivity analysis on key variables, diagnostic testing and calibrating the network, if needed. For this purpose, sensitivity to findings and prediction performance metrics were used to evaluate BN model accuracy (Semakula et al., 2016); e.g. identifying which combinations of EbA interventions – referred to here as scenarios – are likely to be the most successful in contributing positively to community wellbeing. As our BN model combines evidence from multiple different sources, it is critical to know which BN parameters influence the estimation most, or which parameter uncertainties most affect the decision uncertainty (Jackson et al., 2019). Besides, it is important to identify and prioritise the need for further data collection.

Sensitivity analysis calculates to what extent changes in model variables influence the variable of interest within the model (Forio et al., 2015) and helps with validating the probability parameters of a BN model

(BayesFusion, 2020). Both the Netica (Norsys, 2018) and GeNIe (BayesFusion, 2020) packages were used to calculate the sensitivity of community wellbeing to states of key variables in the BN model, which were then quantified through mutual information (entropy reduction). Identification of the most effective actions would provide invaluable information to decide where to spend time and resources in achieving improved outcomes.

Scenarios

Scenario testing is a way to deal with complexity and uncertainty to guide decision support. We constructed and tested 16 EbA intervention scenarios, grouped under two climate change warming scenarios (below and above 1.5 ºC) to explore the impacts of interventions, together with the associated economic costs and their implications for community wellbeing (Table 1). Our scenarios build on the series of EbA interventions detailed in Buckwell et al. (2019) and summarised in Section 1. We tested a range of combinations of the EbA components, in addition to testing all the individual EbA components together in an integrated intervention (Table 1).

Table 1 A range of scenarios used to test the impact of EbA intervention on *Community wellbeing*

We chose above and below 1.5 ºC of warming for our scenarios as the climate change literature indicates this as a significant threshold level of warming for many SIDS and the continued health of the world's coral reefs (Hughes et al., 2017; IPCC, 2014). In our Vanuatu context, if global warming exceeds 1.5 ºC, coral reefs - and specifically the ecosystem services they provide, particularly provisioning services (food; materials) and coastal protection services - are likely to be catastrophically compromised. Vanuatu coastal communities rely directly on these ecosystem services for significant elements of their wellbeing (Buckwell et al., 2019; Mackey et al., 2017). Coral reef cover is highly vulnerable to being damaged irreversibly (Hafezi et al., 2020), and widespread, global loss of coral reefs (above 1.5 ºC) will directly compromise community wellbeing through a range of our BN nodes and will also indirectly impact on other elements of wellbeing by placing greater pressure on substituting ecosystem services from subsistence gardens and forests (Table 1).

Results

Fig 2 shows our final BN model in which states of each node are shown as bars representing the probability of the states for each node, prior to intervention. The target node, *Community wellbeing*, presents the predicted probability of the level of wellbeing in a community being either *Acceptable* or *Unacceptable*.

Fig 2 Bayesian Network model for Community wellbeing in four locations (Grey boxes: Exogenous factors; Green boxes: Ecosystem stocks; Blue boxes: Implementation factors; Orange boxes: Key intervention factors; Pink boxes: EbA interventions and locations

An *Acceptable* level of wellbeing refers to the probability of members of the community having the support needed for their health, safety and resilience in hard times. This also indicates (probabilistically) whether the community is heading in the right direction in terms of achieving community wellbeing in a specific location (e.g. Tanna, Port Vila etc.). The final BN model was used to investigate the effect of a range of EbA options grouped under two climate scenarios, below and above 1.5 ºC of warming (Table 1).

Model evaluation

The performance of our BN model was tested using sensitivity and prediction accuracy metrics. First, the model was evaluated using the built-in 'test only' validation method provided by the GeNIe package (BayesFusion, 2020). The test only method fits circumstances when the BN model is built based on experts' opinion. Table_Sup 2 (confusion matrix) shows validation results for the *Community wellbeing* node in terms of the number of correctly and incorrectly identified instances. The results show that the BN prediction accuracy achieved during the validation process is 79.7% in predicting the correct level of (Acceptable or Unacceptable) *Community wellbeing.* In another words, sensitivity (true positive rate) of our BN model in predicting the *Community wellbeing* is 81.9%, with specificity (true negative rate) at 74.9%.

A sensitivity analysis is useful to identify inputs of a BN model that cause uncertainties in BN outputs. Findings (probability distributions) of all other nodes, except target node and CPTs (parameters), are the two key inputs of BNs. Therefore, two types of sensitivity analyses, sensitivity to findings and sensitivity to parameters, can be performed to determine the importance of nodes. The first reveals how changes in the probability distribution of other nodes would influence the probability distribution of the target node. The latter exposes how sensitive the probability distribution of the target node is to changes in other parameters.

To test the robustness of the output probabilities of our BN model, a sensitivity analysis was conducted by using built-in GeNIe sensitivity analysis (BayesFusion, 2020) based on an algorithm suggested by Kjærulff and van der Gaag (2000). The algorithm identifies all parameters to which an output probability of the *Community wellbeing* (target node) is particularly sensitive. As shown in Fig 3, the colours of identified parameters change (grey to red) to illustrate the locations of these sensitive parameters. Red colour shows the variables to which the output node of the BN model is most sensitive. The sensitivity of grey coloured variables is zero, indicating that these parameters do not influence the output probability of the target node. As shown in Fig 3, the most influential variables change depending on location. For example, "Wealth", "Education", "Health", "Kastom", "Cash income" and "Capital availability" were identified as the most influential variables for Tanna (Fig 3 a), however, in Port Vila, the importance of these variables diminished.

Fig 3 Comparison of the sensitivity of '*Community wellbeing*' to changes at other nodes at two different locations, (a) Tanna and (b) Port Vila. The colouring of the network shows where the sensitive nodes (red) are located based on their degree of influence on the '*Community wellbeing'* node

Finally, the sensitivity to findings was calculated using Netica (Norsys, 2018). To do this, the variables were ranked according to their level of influence on '*Community wellbeing'.* As presented in Fig 4, a high entropy reduction value indicates variables with higher levels of uncertainty (e.g. "Health), while smaller values show less uncertain variables (e.g. "Health care") in the BN model.

Fig 4 Sensitivity of *Community wellbeing* to findings in the form of mutual information (entropy reduction). Variables are displayed in rank order by their degree of influence on *Community wellbeing*

Scenario testings

The final BN model was used to evaluate the effects of sixteen alternative combinations of EbA intervention scenarios on the probability distributions of *Community wellbeing* for the four case study locations. The results show that, as far as *Community wellbeing* is concerned, the most effective scenarios are those that combine all six EbA interventions represented by Scn (scenario) 7 and Scn15, while the *No intervention* scenarios (Scn8 and Scn16) represent the worst outcome.

As shown in Table 2 and Fig_Sup 3, the *Combined ALL* option most significantly increases the probability of an *Acceptable* level of *Community wellbeing* in Port Resolution, under both the below and above 1.5 ºC scenarios (Scn7 and Scn15). In contrast, the benefits of standalone EbA interventions *Marine-community conservation areas* (Scn1 and Scn9), *Forest-community conservation areas* (Scn2 and Scn10), and *Subsistence farming productivity* (Scn4 and Scn12) are all relatively smaller, ranging from 8% to 23%. *No interventions*, under both below and above 1.5 ºC scenarios, result in conditions where *Community* *wellbeing* is, on balance, *Unacceptable*. This highlights the importance of the interventions regardless of the climate change scenario and highlights the need for ecosystem sensitive interventions to support ongoing livelihoods and wellbeing.

Table 2 Posterior probability distributions - Community Wellbeing (%)

Intervention outcomes costs

The costs of implementing EbA options were analysed using data from a separate benefit-cost study[2] (Buckwell et al., 2019). Due to the deterministic nature of the benefit-cost analysis, uncertainty is not usually taken into account, which consequently, may result in a positive net benefit from management actions. As discussed above, the BN model accounts for this uncertainty. Thus, BN models could help to "identify and visualise which assumptions dominate uncertainty surrounding the cost-benefit analysis" (Barton et al., 2008) and therefore, enhance the outcome of benefit-cost analysis.

Buckwell et al. (2019) determined programme costs for the implementation of the modelled EbAs for Tanna. We scaled these costs both up and down for appropriate estimations of costs of implementation at the local scale (Port Resolution), the national scale (Vanuatu) and for Vanuatu's major urban centre, Port Vila. These estimates are summarised in Table 3. We have determined total costs and costs per person at each of the implementation scales. Using these estimates, we calculated the marginal cost of each increment of improvement of community wellbeing for each intervention program scenario, above and below the 1.5 ºC climate change futures (Table 3).

[2] In the cost benefit analysis from Buckwell et al. (2020), the authors estimate costs in terms of programme need and benefits in terms of ecosystem service benefit on a per hectare per year basis. Our BN considers only programme costs, taken on an island by island needs basis, determined mainly by the population requirements, so therefore we use a per person cost of programme implementation.

Table 3 Marginal costs of improvements in the probability of achieving an acceptable level of wellbeing, as estimated by the BN model. We estimate marginal costs for the implementation of all combinations of our ecosystem-based adaptation approaches for two global climate scenarios: (i) where global temperature increases stay below 1.5 ºC above pre-industrial levels; and (ii) where global temperatures exceed 1.5 ºC. Green comparison bars are to the same scale (for Tanna, Port Vila, and Vanuatu). Red comparison bars for Port Resolution are to an alternative scale

Additional spending on implementation of more components of the proposed program (for example, the addition of the community ranger scheme to the community conservation area program) generates greater improvements in wellbeing. However, this comes at a greater per unit per person cost than the simple implementation of the community conservation program. The implementation of all facets of the program generates the greatest improvement in wellbeing but comes at the greatest unit cost per person.

Our BN model results indicate that the optimal scale for program implementation is at the island scale. Localised implementation, for example, at the Port Resolution community scale, is considerably more costly per unit per person than for Tanna (the scale benefits of the radio station, for which costs are attributed to the intervention, are not maximised). However, localised piloting of the EbA projects at the village-scale is undoubtedly beneficial and would form part of any detailed project design.

Discussion

Climate change is the most significant threat to the ecosystems (Weiskopf et al., 2020), wellbeing and livelihoods of people across Vanuatu, including in Port Vila (Mackey et al., 2017). Specific climate change impacts for Vanuatu include a greater propensity for more intense disruptive events, such as more damaging tropical cyclones and coral bleaching events, and chronic impacts, such as sea-level rise, changing rainfall and temperature variability that alters staple food crop growing conditions (Mackey et al., 2017). Assessing the risks climate change brings to community wellbeing, and how adaptation interventions can help mitigate these risks, can be investigated through a SES framing. While additional risks associated with non-climatic threats, especially volcanic activity and tectonic activity, threaten communities on Tanna Island and

Vanuatu, these were not included in our modelling efforts because our focus was to explore how and why ecosystem-based climate change adaptation options affect community wellbeing. To do this, we examined the inter-relationships between a set of key variables to assess the cost-effectiveness of different combinations of EbA interventions in mitigating potential impacts on community wellbeing under a changing climate.

Our model includes both acute and chronic impacts of climate change, in particular the impact of coral bleaching and the potential loss of Vanuatu's fringing coral reefs. These reefs provide substantial ecosystem services for local communities, including direct use, provisioning ecosystem services, especially in-shore, mostly subsistence, artisanal fisheries; indirect regulating ecosystem service uses, such as coastal protection of infrastructure assets from wave energy and carbon sequestration in the calcite growth of corals; and cultural ecosystem services, particularly tourism and recreation; representing significant economic value (Buckwell et al., 2020). Our results suggest that all proposed EbA interventions will have a positive impact on the baseline wellbeing value in all case study locations, to some degree, by either directly improving the integrity of Vanuatu's ecosystems, or by protecting these ecosystems as a positive spill-over from related actions. The positive correlation between wellbeing and ecosystem integrity is supported in the literature, particularly where communities rely directly and acutely on ecosystem services for their day-to-day material needs (Buckwell et al., 2020; Mackey et al., 2017). Combining all interventions generates the greatest increase in wellbeing. Of the two elements of community conservation projects, implementation of the forest-based projects generates greater wellbeing than the marine-based CCAs. Though there are some differences between implementation of the EBAs across the different scales (particularly for implementation of CCAs), the predicted improvements are relatively stable across all scales.

Program costs associated with improvements in community wellbeing face diminishing marginal rates of return on investment, i.e. it costs more to deliver an additional unit increase in wellbeing as the level of wellbeing increases. Diminishing marginal returns on investment is a leitmotif of the economics literature (Brue, 1993) and that our model reports this phenomenon should not be a surprise. Though the components are designed to complement one another, greater implementation complexity is inevitably related to the scope and the scale of all EbAs and potential program donors need transparency of this fact.

Our model included a threshold global temperature increase of 1.5 ºC above pre-industrial level as a state of *Climate* node, on the basis of evidence suggesting degradation of between 70-90% of cover anticipated if this threshold is breached (Hughes et al., 2017). In a 1.5 ºC warmer world, our marginal unit cost per person for all our EbA interventions increases – there is less improvement in wellbeing for the same program expenditure. This marginal cost increase is greatest (proportionally) for implementation of marine CCAs - a 20% increase in marginal cost across Vanuatu (Table_Sup 3). This value is considerably less for Port Vila (+7.7%). The increase in the marginal unit cost of improvements in wellbeing per person is lowest when all programs are implemented (+3.3%), suggesting that full program delivery provides greater insurance against the impacts of a >1.5 ºC rise in global temperatures by increasing adaptive capacity.

Table 2 demonstrates that implementation of EbAs focussed on community-based management of forests and fringing reefs and the introduction of demonstration plots to improve the productivity of subsistence gardens can be effective in improving community wellbeing in urban settings. Thaman (1995) and Thaman et al. (2006) describe the likely and growing contribution of urban agriculture to food security in Pacific SIDS and urbanising Ni-Vanuatu (temporary or permanent). Table_Sup 3 demonstrates that implementation of the proposed EbA programs is most cost-effective in these urban areas, benefiting from logistical efficiencies and likely skilled practitioners. The benefit of improving wellbeing through urban food production is a global phenomenon with a long heritage, with many drivers, of which food security is just one (Eigenbrod and Gruda, 2015; Reader, 2005). As the Ni-Vanuatu become increasingly urbanised, food will be increasingly exchanged for cash. Already, Vanuatu is a significant net importer of food, hence many food prices are subject to price spikes as a result of exchange rate fluctuations. Improving Ni-Vanuatu *urban* communities' resilience to food insecurity will offer significant benefits in the future.

Results from the social cost benefit analysis undertaken by Buckwell et al. (2019) revealed a significant return on investment (benefit-cost ratio, or the value of project benefits divided by project costs, discounted over the duration of the project) for the subsistence garden plus nursery plus radio station components over a 25-year period. The benefits from the implementation of the CCA plus Community Ranger project revealed a significantly lower but positive return on investment and from a significantly lower initial investment. Our BN results, which also inherently include understandings around Kastom, connections and emancipatory values of community members, including women, concur, predicting greater improvements in community wellbeing to EbA interventions that include subsistence gardens components. Whilst the efficacy of both BN and cost-benefit analysis as decision support tools are limited by the availability of data and subject to the sensitivity of the assumptions, both independently and together, they can provide decision-makers with useful perspectives for evaluating project proposals to determine where and when resources can be focussed to provide the most significant improvements in wellbeing from limited resources.

Conclusion

Our study used a BN model and associated analyses to demonstrate how each component of a series of coordinated and complementary EbA approaches can improve community wellbeing at multiple scales, including in both a rural village setting and an urban setting, for Vanuatu. Through describing the nature and the strength of relationships between exogenous drivers and institutions, natural resource stocks and flows, income sources and community facilities, we were able to assess the impact of four proximate determinants (Kastom, Health, Education and Wealth) on increasing the level of acceptable community wellbeing in a future under climate change where global temperatures remain below a 1.5°C increase on pre-industrial levels and when they do not. The EbA components have multiple impacts through complex social (health and education), ecological, institutional, and economic and financial inter-relationships, including those not traditionally associated with EbA programmes of work that have tended to focus on the implementation of nature-based solutions. For EbA to be successful, it needs to have a positive influence through Kastom, Health, Education and Wealth and needs to recognise that the local scale of implementation is not just a geographical location, but a SES (Buggy and McNamara 2016). Using previously costed estimates for the implementation of these EbA approaches we were also able to calculate the marginal costs of improvements in wellbeing and conclude that if global temperatures do exceed the 1.5ºC threshold at which coral reefs, in particular, become severely at risk, the costs of maintaining satisfactory levels of community wellbeing increase.

Given the lack of global progress towards reducing greenhouse gas emissions in line with the Paris Agreement's global warming goals and the growing emissions gap (UNEP, 2019), prospects for limiting global warming to less than 1.5ºC above pre-industrial levels are diminishing. If the impacts of climate change on the wellbeing of communities in Pacific SIDS are to be mitigated and resilience to environmental change for rural communities is to be supported, EbA approaches that improve food production (or reduce food insecurity), whilst also alleviating pressure on remaining natural habitats, provide potentially fruitful avenues and should be considered a high priority for major donors and project sponsors.

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	Number of child nodes	Community wellbeing	Health	Wealth	Nutrition	Non-cash economy	Kastom	Institutional recognition of Kastom	Health Care	Western medicine acceptance	Education	Participation	Education facilities	Cash income	Remittance	Tourism income	Fish catch	Forest condition	Subsistence farming production	Potable water	Coral reef condition	EbA Interventions	Development regulations	Climate	Scenarios	Capital availability	Public service capacity	Population growth	Locations
Number of parent nodes		4	4	2	9	8	4	1	14	2	2	1	4	7	1	10	3	6	7	6	4	1	0	1	0	1	1	1	0
Community wellbeing	0																												
Health	1	x																											
Wealth	1	x																											
Nutrition	1		x																										
Non-cash economy	2			x	x																								
Kastom	1	x																											
Institutional recognition of Kastom	1						x																						
Health Care	1		x																										
Western medicine acceptance	1								x																				
Education	3	x	x							x																			
Participation	1										x																		
Education facilities	1										x																		
Cash income	5			x	x	x			x			x																	
Remittance	3				x	x								x															
Tourism income	4				x	x			x					x															
Fish catch	3				x	x								x															
Forest condition	6				x	x	x		x					x		x													
Subsistence farming production	6				x	x			x					x		x		x											
Potable water	4		x						x							x			x										
Coral reef condition	5						x		x							x	x	x											
EbA Interventions	10				x	x			x					x		x	x	x	x	x	x								
Development regulations	6								x							x		x	x	x	x								
Climate	6								x							x		x	x	x	x								
Scenarios	3							x														x		x					
Capital availability	6								x				x		x	x			x	x									
Public service capacity	5								x				x			x			x	x									
Population growth	8								x				x			x	x	x	x	x	x								
Locations	10				x	x	x		x	x			x	x												x	x	x	

Legend
- Target node
- Intervention factors
- Implementation factors
- EcoSystem stocks
- Exogenous factors
- EbA interventions

Figure2

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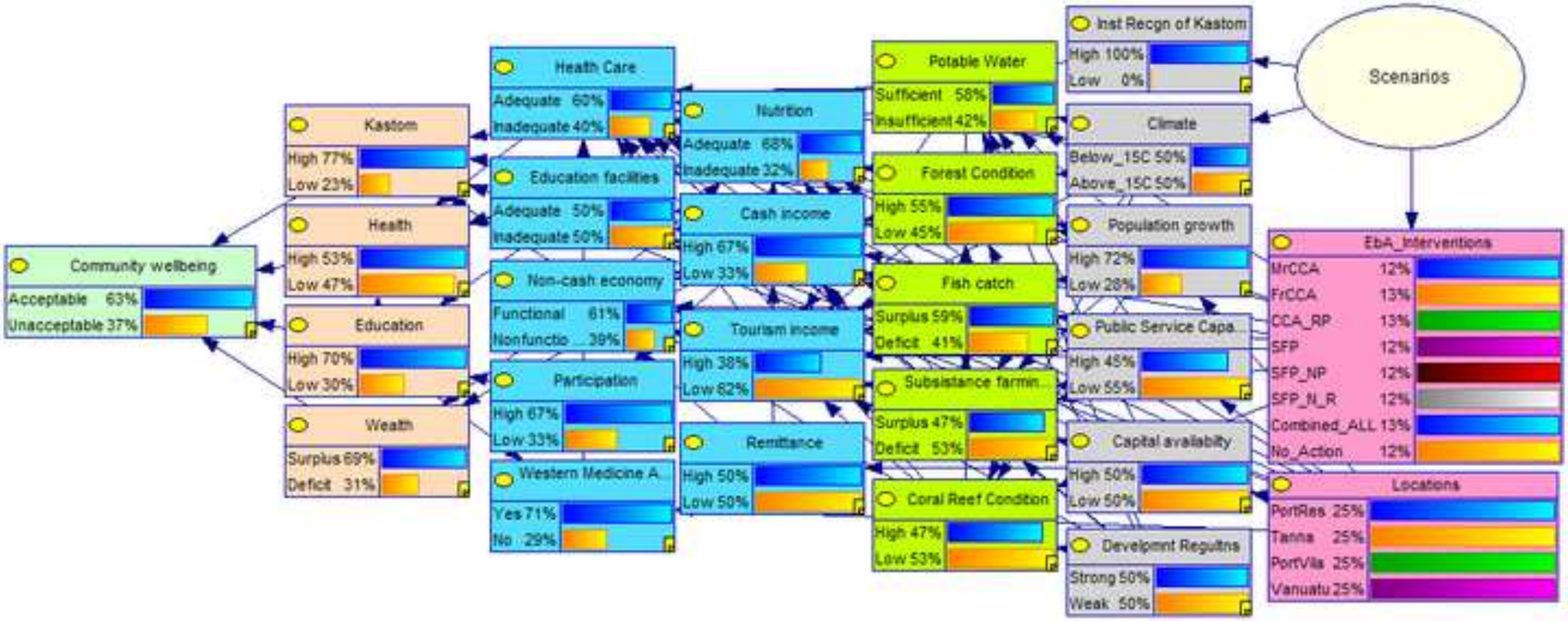


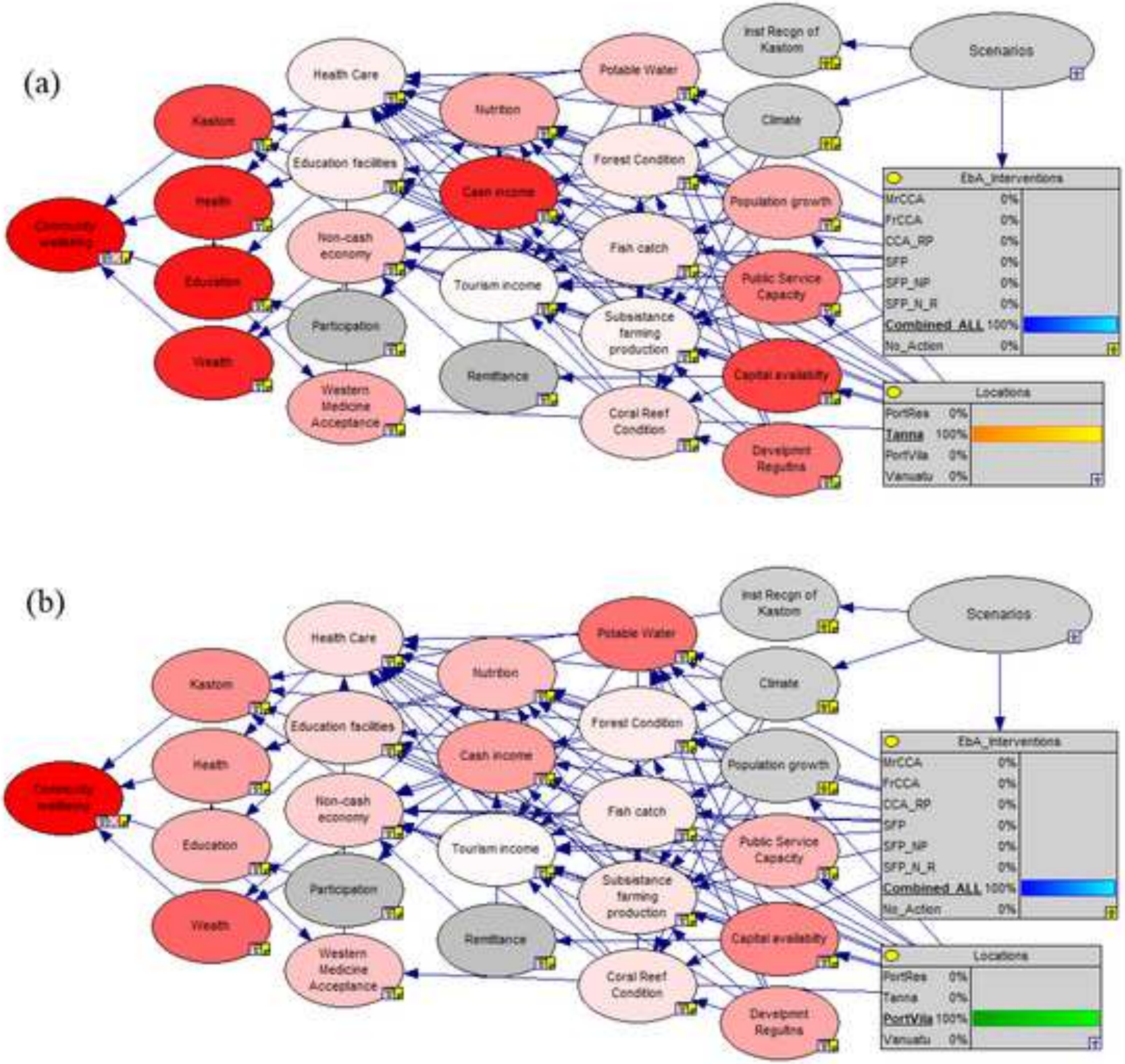
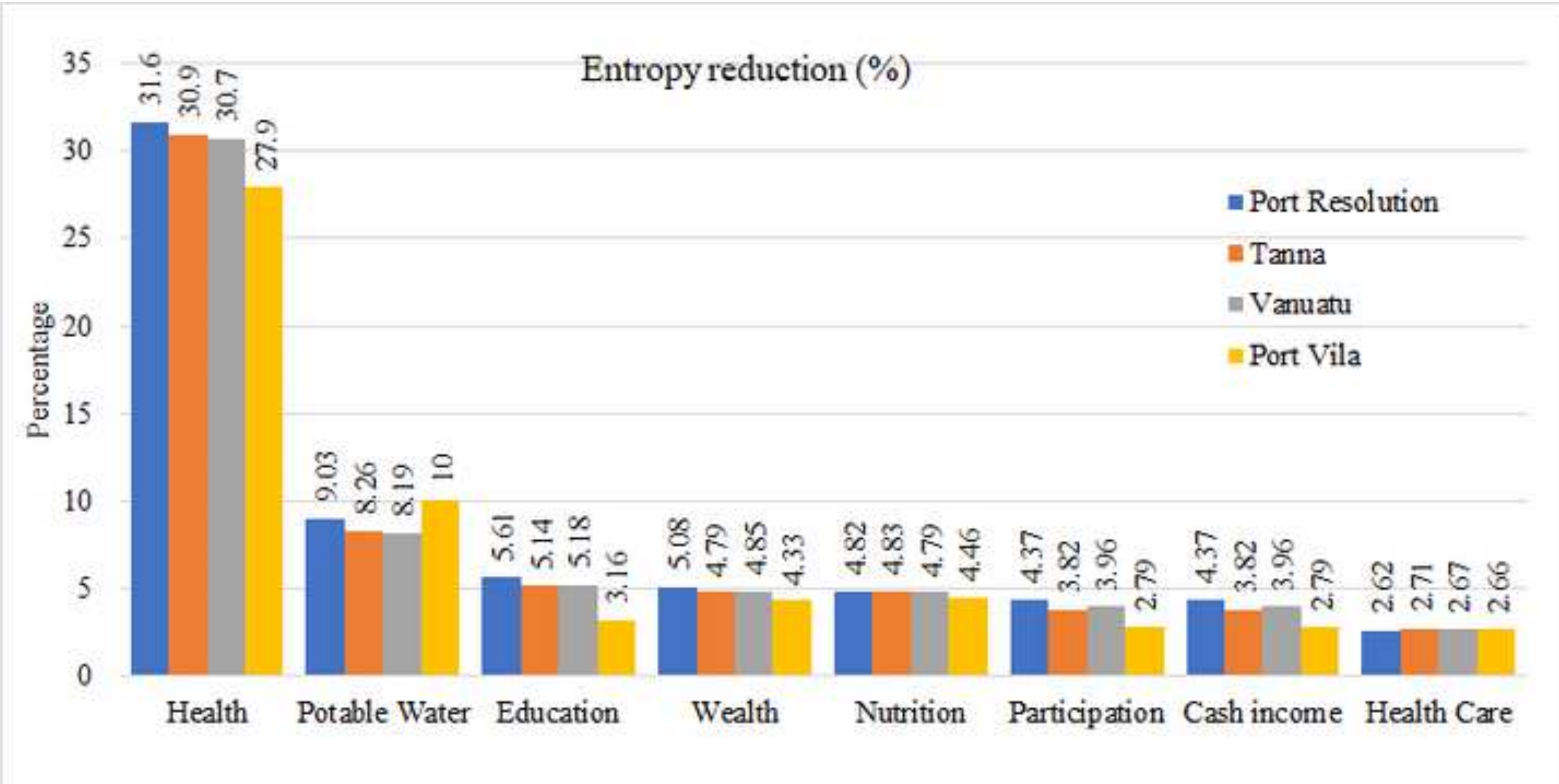

(a)
Health Care
Kastom
Nutrition
Potable Water
Inst Recogn of Kastom
Scenarios
Climate
Education facilities
Health
Forest Condition
Community wellbeing
Cash income
Population growth
EbA_Interventions
MrCCA 0%
FrCCA 0%
CCA_RP 0%
SFP 0%
SFP_NP 0%
SFP_N_R 0%
Combined_ALL 100%
No_Action 0%
Non-cash economy
Fish catch
Education
Public Service Capacity
Tourism income
Participation
Subsistance farming production
Wealth
Capital availability
Remittance
Locations
PortRes 0%
Tanna 100%
PortVila 0%
Vanuatu 0%
Western Medicine Acceptance
Coral Reef Condition
Develpmnt Regultns
(b)
Health Care
Kastom
Nutrition
Potable Water
Inst Recogn of Kastom
Scenarios
Climate
Education facilities
Health
Forest Condition
Community wellbeing
Cash income
Population growth
EbA_Interventions
MrCCA 0%
FrCCA 0%
CCA_RP 0%
SFP 0%
SFP_NP 0%
SFP_N_R 0%
Combined_ALL 100%
No_Action 0%
Non-cash economy
Fish catch
Education
Public Service Capacity
Tourism income
Participation
Subsistance farming production
Wealth
Capital availability
Remittance
Locations
PortRes 0%
Tanna 0%
PortVila 100%
Vanuatu 0%
Western Medicine Acceptance
Coral Reef Condition
Develpmnt Regultns

Figure4


Entropy reduction (%)
Percentage
35
30
25
20
15
10
5
0
31.6
30.9
30.7
27.9
9.03
8.26
8.19
10
5.61
5.14
5.18
3.16
5.08
4.79
4.85
4.33
4.82
4.83
4.79
4.46
4.37
3.82
3.96
2.79
4.37
3.82
3.96
2.79
2.62
2.71
2.67
2.66
Health
Potable Water
Education
Wealth
Nutrition
Participation
Cash income
Health Care
Port Resolution
Tanna
Vanuatu
Port Vila

~~Table 2~~ Table 1 A range of scenarios used to test the impact of EbA intervention on *Community wellbeing*

		Climate													
		t< 1.5 C							t> 1.5 C						
Scns	Definition	MrCCA	FrCCA	RP	SFP	Nursery	Com Radio	No Action	MrCCA	FrCCA	RP	SFP	Nursery	Com Radio	No Action
Scn1	Marine - community conservation areas	x													
Scn2	Forest - community conservation areas		x												
Scn3	Community conservation areas & Ranger program	x	x	x											
Scn4	Subsistence farming productivity				x										
Scn5	Subsistence farming productivity & Nursery program				x	x									
Scn6	Subsistence farming productivity & Nursery program & Community radio				x	x	x								
Scn7	Combined ALL	x	x	x	x	x	x								
Scn8	No intervention							x							
Scn9	Marine - community conservation areas								x						
Scn10	Forest - community conservation areas									x					
Scn11	Community conservation areas & Ranger program								x	x	x				
Scn12	Subsistence farming productivity											x			
Scn13	Subsistence farming productivity & Nursery program											x	x		
Scn14	Subsistence farming productivity & Nursery program & Community radio											x	x	x	
Scn15	Combined ALL								x	x	x	x	x	x	
Scn16	No intervention														x

MrCCA:Marine community conservation areas; FrCCA: Forest community conservation areas; RP: Ranger program; SFP: Subsistence farming productivity; Nursery:Nursery program; Com Radio: Community radio

Table2

~~Table 4~~Table 2 Posterior probability distributions - Community Wellbeing (%)

	Scns	Definition	Port resolution Acceptable	Port resolution Unacceptable	Tanna Acceptable	Tanna Unacceptable	Port Vila Acceptable	Port Vila Unacceptable	Vanuatu Acceptable	Vanuatu Unacceptable
Below 1.5 C	Scn1	Marine - community conservation areas	53	47	51	49	63	37	56	44
	Scn2	Forest - community conservation areas	61	39	55	45	70	30	62	38
	Scn3	Community conservation areas & Ranger program	66	34	65	35	75	25	68	32
	Scn4	Subsistance farming productivity	66	34	64	36	71	29	67	33
	Scn5	Subsistance farming productivity & Nursery program	67	33	67	33	73	27	69	31
	Scn6	Subsistance farming productivity & Nursery program & Community radio	74	26	76	24	78	22	76	24
	Scn7	Combined ALL	77	23	78	22	80	20	77	23
	Scn8	No intervention	43	57	45	55	49	51	44	56
Above 1.5 C	Scn9	Marine - community conservation areas	49	51	47	53	59	41	52	48
	Scn10	Forest - community conservation areas	57	43	52	48	66	34	58	42
	Scn11	Community conservation areas & Ranger program	60	40	60	40	69	31	62	38
	Scn12	Subsistance farming productivity	61	39	60	40	66	34	62	38
	Scn13	Subsistance farming productivity & Nursery program	63	37	63	37	69	31	65	35
	Scn14	Subsistance farming productivity & Nursery program & Community radio	70	30	72	28	74	26	71	29
	Scn15	Combined ALL	73	27	75	25	77	23	74	26
	Scn16	No intervention	41	59	43	57	46	54	42	58

Table3

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Geographic scale	Port Resolution				Tanna				Port Vila				Vanuatu			
Scenario	Level of acceptable well-being	Improvement in acceptable level of well-being from no intervention baseline	Marginal cost of improvements in well-being	Difference in marginal cost of improvement in well-being above and below 1.5 degrees	Level of acceptable well-being	Improvement in acceptable level of well-being from no intervention baseline	Marginal cost of improvements in well-being	Difference in marginal cost of improvement in well-being above and below 1.5 degrees	Level of acceptable well-being	Improvement in acceptable level of well-being from no intervention baseline	Marginal cost of improvements in well-being	Difference in marginal cost of improvement in well-being above and below 1.5 degrees	Level of acceptable well-being	Improvement in acceptable level of well-being from no intervention baseline	Marginal cost of improvements in well-being	Difference in marginal cost of improvement in well-being above and below 1.5 degrees
Global temperature increase stays below 1.5 degrees																
Marine CCA	53	10	$42.90		51	6	$2.46		63	14	$0.44		56	12	$2.12	
Forest CCA	61	18	$23.83		55	10	$1.48		70	21	$0.30		62	18	$1.41	
CCA + Ranger	66	23	$24.18		65	20	$1.49		75	26	$0.83		68	24	$1.82	
Demo plots	66	23	$51.28		64	19	$3.01		71	22	$2.60		67	23	$3.18	
Demo plots + nursery	67	24	$73.10		67	22	$3.03		73	24	$2.67		69	25	$3.80	
Demo + nursery + radio	74	31	$133.64		76	31	$3.09		78	29	$2.83		76	32	$3.22	
Combined all	77	34	$138.20		78	33	$3.80		80	31	$3.34		77	33	$4.44	
No intervention	43				45				49				44			
Global temperature increase goes above 1.5 degrees																
Marine CCA	49	8	$53.62	$10.72	47	4	$3.69	$1.23	59	13	$0.48	$0.03	52	10	$2.55	$0.42
Forest CCA	57	16	$26.81	$2.98	52	9	$1.64	$0.16	66	20	$0.31	$0.01	58	16	$1.59	$0.18
CCA + Ranger	60	19	$29.27	$5.09	60	17	$1.75	$0.26	69	23	$0.94	$0.11	62	20	$2.19	$0.36
Demo plots	61	20	$58.97	$7.69	60	17	$3.37	$0.36	66	20	$2.86	$0.26	62	20	$3.66	$0.48
Demo plots + nursery	63	22	$79.74	$6.65	63	20	$3.34	$0.30	69	23	$2.79	$0.12	65	23	$4.13	$0.33
Demo + nursery + radio	70	29	$142.85	$9.22	72	29	$3.30	$0.21	74	28	$2.93	$0.10	71	29	$3.55	$0.33
Combined all	73	32	$146.84	$8.64	75	32	$3.92	$0.12	77	31	$3.34	$ -	74	32	$4.58	$0.14
No intervention	41				43				46				42			

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Figure_Sup 2.tif