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An introduction to Bayesian networks as assessment and decision support tools for managing coral reef ecosystem services

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Abstract

Quantifying ecosystem goods and services can help evaluate policies aimed at protecting present and future generations from losing ecosystem benefits. Explicating and quantifying the relationships among risk factors, ecological structure and function, and delivery of ecosystem goods and services requires analytical methodologies that propagate uncertainties. The capabilities of Bayesian networks in generating predictions and accounting for uncertainty are explored with a focus on coral reef ecosystem service assessments. The qualitative aspects of Bayesian networks can be applied to conceptual frameworks developed for coral reef ecosystem service assessments. This is demonstrated using qualitative graphs that describe the relationships between coral reef condition endpoints and benefits from ecosystem services including property protection, recreational opportunities, fish for fisheries, and biochemical metabolites for commercial products developed from reef organisms. Bayesian networks help weigh uncertainties between management decision impacts on stressors and the corresponding delivery of ecosystem services. Quantitative capabilities for inferences are examined in hypothetical scenarios evaluating how decisions affect coral reef ecosystem services and economic benefits and resilience to episodic stress. The described methods facilitate visualizing the potential impacts on ecosystem services from alternative scenarios.

Keywords

Coral reefs; ecosystem services; total economic value; probability; uncertainty; Bayesian networks

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1. Introduction

The ecosystem services (ES) field of research is a growing science with overlapping disciplines and broad specialties. Over the last decade, consideration of impacts on ES has undoubtedly played a much greater role in environmental management (reviewed in Costanza et al. 2017). However, knowledge of the benefits provided by ecosystems and how structural and functional characteristics of ecosystems relate to the provision of benefits remains highly uncertain (Fisher et al. 2009; Pérez-Miñana 2016). As the National Research Council (NRC 2005) states, “given the imperfect knowledge of the way people value natural ecosystems and their goods and services, and our limited understanding of the underlying ecology and biogeochemistry of aquatic ecosystems, calculations of the value of the changes resulting from a policy intervention will always be approximate.” Adopting approaches that explicitly account for uncertainties will allow practitioners to transparently characterize the lack of knowledge in a problem, and to consider variance, conflicts in evidence, and the noise inherent in most real-world economic and environmental data.

The application of Bayesian networks (BNs) has experienced recent growth in environmental management applications (Landuyt et al. 2013). Bayesian networks can represent the uncertainties from existing data and knowledge and provide a capable tool for adaptive procedures in highly uncertain decision-making environments. Bayesian networks are graphical models of random variables linked by arrows that represent a dependency, which is sometimes a cause and effect relationship, between variables. Each random variable has a probabilistic function to quantify the effects of the parent node(s) on that variable (Pearl 1988). The use of BNs has been prompted by a growing demand for analytical tools to solve complex problems that are broad, multi-disciplinary, require greater accountability to stakeholders, and account for uncertain data and outcomes. Coupling BNs with ES assessments can provide new opportunities to assess the uncertainty of ES outcomes in the context of multi-dimensional management decisions.

Recently, Landuyt et al. (2013), in their literature review, provided guidance on how and when BNs can be useful for ES assessments. They concluded that the full capabilities of BNs have not been considered, especially in the development of models that explicitly incorporate both costs and benefits from decision-making. Bayesian networks have been used to conduct ES assessments for a variety of different applications, including forest management (Grêt-Regamey et al. 2013), water resources (Barton et al. 2008; Spence and Jordan 2013; Landuyt et al. 2014), agriculture (Poppenborg and Koellner 2014), and marine planning (Stelzenmüller et al. 2010). The full potential of BNs remains underutilized, however, with existing applications typically focusing on a single ES endpoint, and often more specifically on ecological processes where data and underlying processes are fairly well understood (Landuyt et al. 2013). To date the application of BNs to coral reef ES assessments has been limited despite the importance of ES from coral reefs to many beneficiaries across the world, including natural products development, tourism and recreation opportunities, and coastal protection (Principe et al. 2012), and the increasing threats to their future integrity.

This article explores how BNs might be developed to examine potential impacts of threats and management activities on coral reef ES. Though developed for coral reefs, the examples illustrate how BNs can be used to address several ongoing challenges in applying BNs to conduct ES assessments, including i) the potential to use BNs to tackle ES that are often poorly understood but highly valued (Broekx et al. 2013), ii) to adopt integrated approaches for considering uncertainties in the production of multiple ES (Landuyt et al. 2013), and iii) to more fully consider the cascade of ES delivery from ecological condition to value (Haines-Young and Potshchin 2010). To illustrate these concepts, examples of uncertainties related to stressors, coral reef condition, and ES production of reef systems are given. Valuation of ES can be combined with BNs to characterize uncertainties and better support decision making.

2. Defining ecosystem services relationships using BNs

2.1. Classifying Services for Causal Inference

Classifying ES under a single scheme is difficult because of the variety of contexts and sources of evidence that must be considered in an ES assessment (Fisher et al. 2009). Additionally, many ES classification schemes intermix means (intermediate ES) with ends (final ES), which can confound proper valuation (Wallace 2007). To avoid ‘double-counting’, Boyd and Banzhaf (2007) define final ES as “components of nature directly enjoyed, consumed, or used to yield human well-being”. That is, final ES are tangible components of the ecosystem that are related directly to the benefits (Landers and Nahlik 2013). Fisher et al. (2009) expanded this into also considering final ES as ecosystem processes, along with components, for designating final ES. Probabilistic networks can help to conceptualize and communicate the difference between intermediate and final ES, and can also account for human inputs, such as labor, needed to realize the benefits of ES. The final ES are important to consider when evaluating the benefits from an ecosystem. Their identification for decision analysis or ecosystem assessments is not always straight forward and must take into account the benefits the ecosystem provides, supported by considerations of the assessment or decision context, indications from market transactions, values of stakeholders, use-related information, and sensitivity to the range of policies under consideration (Freeman III 2002; Fisher et al., 2009; Sagoff 2011). Intermediate ES can provide important information for delineating causal relationships among stressors, management interventions, and the final ES.

Predicting final ES outcomes requires consideration of a cascading range of interacting events, including human interventions on stressors and the status of ecological production functions. Ecological production functions are those relationships that connect the biophysical characteristics of ecosystems with the supply of ES (Fisher et al. 2011). Often, the knowledge of the relationship between ecosystem processes and final ES delivery will be incomplete or difficult to estimate (Wallace 2007). Additional uncertainties arise with structural and functional relationships of an ecosystem, the provisioning of goods and services under different environmental and social scenarios, and the value of ES outcomes (NRC 2005). All these uncertainties demonstrate the need for a probabilistic assessment framework. A BN offers a graphical, probabilistic approach to identify the important ES

components and relationships, uncertainties related to ES and other factors important to decision making (Figure 1).

Ecosystem service assessments should be part of a larger decision analysis process that includes other factors beyond ES, such as costs generated by a decision and social equity (Reichert et al. 2007). While our focus here is on how BNs can be structured to support causal inferences for ES assessments, other decision analytic tools and frameworks can be applied to identify an appropriate context, organize attributes and objectives for decisions, assess consequences beyond ES, examine values-based trade-offs, and implement adaptive management using ES assessments (Gregory et al. 2012).

2.2. Levels of Representation in Bayesian Networks

Bayesian networks (aka Bayesian belief networks, Bayes nets, probability networks) are acyclic graphs of random variables with directed links connecting them (Korb and Nicholson 2011). They are directed graphs structured to represent the conditional independence between variables (Kjærulff and Madsen 2013) that can be considered as a tool for applying Bayes' theorem, namely that knowledge of related information can help us calculate the probability of an event. Nodes (typically displayed as circles or boxes) in a BN represent random variables, and arcs (displayed as arrows) are used to indicate a conditional relationship between the parent (originator) and child (receiver) nodes (Pearl 1988). The structure of the BN is of key importance and dictates the relationships that must be quantified in the model. The structures can be developed manually or learned from data or a combination of both. We focus on manually constructed BNs here that have a causal structure. In practice, BNs should graph the correlations among variables in such a manner where knowledge of one or more variables will either block or open knowledge about other variables (Pearl 2009). A BN structure represents these conditional independence relationships among a set of variables. As long as the independence structure between variables is properly represented, the basic conditional independence assumptions for the structure of a BN will be met (Korb and Nicholson 2011).

Bayesian networks have three levels of representation that make them attractive for solving complex problems (Howard and Matheson 2005). A simple example illustrates how these three levels (relation, function, number) might be set up to qualitatively and quantitatively infer effects of ocean acidification on fishing stocks (Figure 2). In this example, fish stocks are dependent on habitat provided by coral reef colonies, the condition and availability of which is influenced by stressors generated through ocean acidification. The first level (relation) reflects these cause-effect relationships, but is not mathematical—the connections in the graph between nodes indicate conditional independence relationships among variables (Figure 2(a)). In this example, fishing stock is assumed conditionally independent of ocean acidification given coral surface area and vice-versa. Based on the structure of the graph and the lack of a direct arc between ocean acidification and fishing stock, the relationship between the two variables is modified by coral surface area. Knowing coral surface area will block any statistical interaction between ocean acidification and fishing stock making them (conditionally) independent. In the context of this model, if it is found that fishing stock could be influenced by ocean acidification (outside of the influence through coral surface

area), an arc could be drawn connecting the two variables directly or additional nodes could be added between the two variables to better explain the relationship. This intuitive structure makes BNs simpler than other complex models for explanation to public stakeholders and non-experts. The direction of the arrows in Figure 2(a) follows a cause and effect flow. Mutually exclusive and exhaustive ordered states of high and low are used to ensure inclusion of the full range of values for a variable and that those values can be exclusively assigned to a comparative category. Variables contain nominal, integer, or continuous scales (Korb and Nicholson 2011).

A second level of representation is function, where probabilistic relationships between different nodes represent the strength of the relationships (Figure 2(b)). Each relationship between a child node and its parent(s) requires a conditional probability. A conditional probability table (CPT) addresses this concept—probabilities can be manually input to the table to quantify the strength of the relationships. In Figure 2(b), the conditional probability tables are given for each state of coral surface area and fishing stock given the possible states of their immediate predecessor nodes. In this example, if ocean acidification is high, then the probability of high coral surface area is 15%; but if ocean acidification is low, the probability of high coral surface area rises to 30%. In practice, the derivation of probabilistic relationships is often domain-specific, requiring expertise in the relationships between variables. Thus, each node can be viewed as a sub-model for the purposes of identifying the best available data sources, mathematical functions, or expert knowledge to establish probabilities (Borsuk 2008). Fenton and Neil (2013) provide background and examples for how CPTs might be derived for diverse fields with expert opinion, model simulations, and data. If the relationships between variables can be defined and expressed as probabilities, a BN can be a helpful structure for representing existing knowledge, such as the existing state of the science, and inferring potential outcomes.

The third level of representation is number, where prior distributions are assigned to nodes without parents that allow computation of the marginal probabilities of the descendants (Figure 2(c)). In Figure 2(c), the root node (node without any parents) for ocean acidification is given a prior probability distribution to represent the uncertainty of whether it is in a high or low state. In the example, the probability that ocean acidification is high is 25%. The prior probabilities from the root nodes allow calculation of the prior probabilities of the children nodes, and so on, until each variable state has a marginal probability before evidence queries are made (Fenton and Neil 2013). Once a BBN is specified with qualitative and quantitative relationships, as in Figure 2(c), it can be queried to examine scenarios where observed variables or new evidence describes the probabilities of unobserved variables (Shachter and Heckerman 1987). Evidence can be input pertaining to the states of nodes anywhere in the network, not just root nodes as demonstrated in this example. These calculations then propagate to upstream and downstream variables in the network, depending on the network structure, existing evidence, and conditional independence relationships between the nodes.

2.3. Using Idioms to Structure Bayesian Networks for Ecosystem Service Assessments

Oftentimes, it can be difficult to select the most useful structure for available information when making inferences in BNs. Generic model fragments, called idioms or “specific BN

fragments that represent very generic types of uncertain reasoning” (Neil et al. 2000), can assist in developing BNs for a variety of problems, including those involving ES. Idioms can be pieced together into cohesive robust BNs that are useful for making inferences (Neil et al. 2000). Five idioms, described in Table 1, can be applied to ES assessments to make causal inferences, assess beliefs about data and model output, and to make measurement uncertainties explicit in the model’s calculations (Kjærulff and Madsen 2008). The cause-consequence idiom, which assesses uncertainties between causes and effects, is the most widespread idiom used in BN modeling (Neil et al. 2000). The definitional idiom clarifies the meaning of a variable through other variables; it can include uncertainty in the definitions but is often deterministic. The measurement, induction, and reconciliation idioms are useful when uncertainties regarding measurements, forecasting from past data, and model assessments need to be evaluated and propagated in the BN (Kjærulff and Madsen 2008). Neil et al. (2000) provide useful guidance for selecting idioms for use in BNs. The cause-consequence idiom is the focus of this paper because of its universal relevance to ecosystem services management and decision making.

3. Examples of Applications of BNs to Coral Reef Ecosystem Services

3.1. Relating Coral Structure and Function to Ecosystem Services

Principe et al. (2012) reviewed linkages between coral reef ecosystems, bio-physical functions, and ecosystem goods and services. A number of methods (Yee et al. 2014) currently exist for identifying coral reef attributes, or measurable aspects of coral reefs, that contribute to final ES. Here, we also incorporate Fisher et al. (2009) in defining final ES as measurable structure or process components of the reef ecosystem that lead to human benefits (e.g., fish for fisheries) but are not yet combined with human labor (e.g., harvesting, processing) for providing those benefits. The linkages between intermediate and final ES imply cause-effect relationships that can be translated into BN diagrams. Example BNs can help illustrate how causal inferences might be derived (cause-consequence idiom, Table 1) and uncertainties in final ES outcomes examined.

Bayesian network diagrams are illustrated (Figure 3) at the relational level for each of five benefits of ES identified in Principe et al. (2012): property protection, tourism and recreation opportunities, fish for fisheries, biochemical metabolites for commercial products, and existence value. The initial structures were based on production functions for coral reef ES that could potentially lead to benefits, as described in Yee et al. (2014). Beyond the production function relationships (solid black arcs), additional relationships that might be necessary to consider for appropriate inferences were identified (gray dashed arcs) based on correlations between coral reef attributes and notions of conditional independence introduced in Section 2.2. Among these benefits of ES, existence value (Figure 3e) may not be intuitively obvious. It is determined by coral reef integrity, the ecological structure and function that embodies a natural coral reef ecosystem, which is expected to have resilience and sustain coral reefs into the future. Conceptual BNs are shown in Figure 3 as an example of characterizing production functions for estimating final ES. Indices of property protection use measures of coral reef habitat types (Mumby et al. 2008), extent, and distance from shore (Burke et al. 2008) to estimate a relative value for coastal protection. Implicit within

these indices, however, are the biophysical properties of coral reefs that attenuate offshore wave energy (Figure 3(a)). Wave energy attenuation by reefs has been described in biophysical models relating how offshore incident waves of a given height and frequency encounter the steep slope of the reef front, then diminish as they move over the width of the reef towards the shore, depending on the degree of roughness, or rugosity, conferred by the type of reef (Sheppard et al. 2005). The degree of wave attenuation will have consequences for rates of beach erosion (Wielgus et al. 2010) and wave run-up onto shore (FEMA 2007), both of which could lead to property damage or loss of life during storm events. Actual outcomes would depend on other properties of the coastline, including coastal development, vegetation such as mangroves, and geology (Burke et al. 2008).

For tourism and recreation (Figure 3(b)), a number of final ES have been identified through surveys of divers (Wielgus et al. 2003; Uyarra et al. 2009). Preferred components of the coral system include fish and coral abundance and richness, presence of schooling fish, and water transparency. Reef structural complexity (e.g., rugosity) is both a final and intermediate ES; in addition to a preferred dive site attribute (Uyarra et al. 2009), it also contributes to fish abundance and richness (Gratwicke and Speight 2005). Coral richness and abundance may be correlated, and are often associated with greater rugosity (Figure 3b; dashed lines). Actual rates of visitation to a dive site will also depend on its accessibility from shore (Pendleton 1994). Water transparency and accessibility are both important for the estimation of benefits from the coral reef ES but are not included in the model since their status is dependent on factors outside of the structure and function of the coral reef ecosystem; they are not dependent on coral reef production functions highlighted in this model. However, models that estimate benefits from the coral reef final ES to human users would include these characteristics.

One proposed indicator of fisheries production (Figure 3(c)) is the biomass of two key commercial fish groups, snappers and groupers (Healthy Reefs Initiative 2010). Reef habitat type (e.g., patch reef, *Montastraea* reef) may determine the density of certain commercial fish species, such as grouper, and overall finfish production (Mumby et al. 2008). Moreover, connectivity between coral reefs and mangroves, which provide essential fish nursery habitat, is known to be a factor influencing fish abundance and is an indicator of fish production (Mumby 2006). If reliable monitoring data on the density of grouper, snapper, and other key species are lacking, total fish abundance may serve as a proxy for the probability of commercially relevant fish species being available and the uncertainties arising from the usage of this proxy might be assessed using the measurement idiom (Table 1).

Sponge diversity is a key intermediate service and a reasonable final ES proxy for biochemical metabolites for commercial products (e.g., natural products such as pharmaceuticals, Figure 3d). Sponge diversity may also be related to the biotic coverage of different habitat types (Mumby et al. 2008). The relationship of sponge diversity to biochemical metabolites for commercial product development may be estimated from historical data and from knowledge of the uncertainties in bringing biologically active molecules to commercial utility. Furthermore, a healthy reef with a high biodiversity index score may increase the probability of generating biochemical metabolites for commercial

products. A number of attributes, including lack of macroalgal cover, fish abundance and richness, and coral cover and richness are considered to be indicative of reef integrity (van Beukering and Cesar 2004). Though treated additively in the calculation of a reef integrity index, in reality these attributes are often correlated (Figure 3d, dashed arrows). These relationships illustrate the definitional idiom of BNs (Table 1). In quantifying reef ecosystem integrity (Figure 3e), multiple methods have been proposed and Bayesian networks may provide one way to reconcile alternative definitions (reconciliation idiom; Table 1).

The key attributes from separate models can then be integrated into a single model (Figure 4). Through this process, we can begin to differentiate intermediate ES that contribute to a number of final ES and can identify gaps in existing methods where additional nodes or arrows may be needed to properly build relationships among variables. For example, reef structural complexity, often measured as rugosity, directly contributes to wave attenuation and dive site quality and indirectly contributes to natural product creation and fish production. It is important to remember that the example models presented here were chosen to illustrate existing methods (reviewed in Principe et al. 2012; Yee et al. 2014). Ideally, BNs should be developed with a combination of existing models and expert knowledge to ensure that relationships among nodes are properly diagrammed and key variables are included.

A probabilistic network linking intermediate reef ES to final ES provisioning (Figure 4) could be used in a number of applications to support decision making. For example, changes in reef condition could be linked to a potential decision scenario, such as the development of a marine protected area. Implementation of the decision could then be linked to the probabilities of changes in reef condition and the corresponding probability of an increase or decrease in total provisioning of ES. A key factor in the predicted distribution of outcomes is tracking the uncertainties throughout the BN. Reducing uncertainty in specific nodes or relationships could improve overall model certainty. One key is to determine the sensitivity of ES predictions to small changes in reef attributes. Sensitivity analysis (Kjærulff and Madsen 2008) addresses this by measuring the effect of small changes in one parameter to the target probability of interest. For example, sparse data on fish richness could dramatically increase uncertainty in predictions of recreational diving benefits, but have minimal effects on overall estimates of bundled ES benefits. In contrast, improving certainty in an attribute such as reef rugosity, could significantly alter the estimation of total ES provisioning due to its role in multiple functions (e.g., wave energy attenuation, habitat provisioning, attractiveness of dive sites). Describing cause-consequence relationships among variables and assigning probabilities to these relationships provides a quantitative process for identifying high-priority reef attributes. These attributes can be targeted for monitoring to improve ES predictions and inform future management decisions.

3.2 Assessing the Impact of a Management Decision

A hypothetical example will demonstrate some of the inferences that might be made in an ES assessment of alternate management decisions. This example considers whether to implement primary, secondary, or tertiary treatment at a sewage plant undergoing renovations (Figure 5). One concern of managers is the impact of nutrient enrichment on algal overgrowth or cultural eutrophication in an adjacent coral reef system. The coral reef is

frequented by divers who value the ES provided by reef structure and the fish and invertebrate species inhabiting the reef. The satisfaction of recreational divers, in this context, is the benefit of concern. The reef state and the diversity of species are both final ES, with reef state also being an intermediate ES to species diversity. The problem can be set up as a BN, using software such as Netica (Norsys 2010) where nodes and arrows represent the conditional relationships of the above variables (Figure 5). For example, the BN structure communicates that reef state is independent from sewage treatment, but conditional on knowledge of nutrient loadings. In other words, if nutrient loadings to the reef are known with certainty, then sewage treatment type gives no additional information on reef state and vice-versa (i.e., conditional independence). However, if nutrient loadings are unknown, information on sewage treatment types can provide information on potential states for nutrient loadings, and subsequent consequences to reef state and dive satisfaction. Kjærulff and Madsen (2008) provide additional descriptions of conditional independence relationships and their importance to proper inferences in a BN.

Categorical values were assigned for node states, while discretized ranges were attached for continuous variables (e.g., nutrient loadings). Discretization, when required, should be done carefully; for example, following known breaking points such as phase shifts in relationships. Discretization issues and potential recommended resolutions for different types of nodes and problems are further discussed in Conrady and Jouffe (2015) and Neil et al. (2007). Probabilities can be established using a variety of methods for conditional (i.e., nodes with parents and a conditional probability table) and unconditional relationships (i.e., root nodes with no incoming arcs). While not reviewed here, these include the range of parametric, semi-parametric and non-parametric tools for developing probability distributions that can incorporate model simulation output, measurement data, and expert opinion. Given the specified underlying conditional probabilities, the BN initially calculates and shows the prior probabilities of each of the variables. For this example, the root node for sewage treatment will have probabilities set to 100% (absolute certainty of occurrence) when testing each of the treatment options (shaded boxes in Figure 5) to assess changes in stressors, reef condition, and dive satisfaction under alternate sewage treatment scenarios. Instantiating or specifying a node's state will update the model predictions to posterior probabilities using probabilistic calculus to examine the impact of this evidence on the other posterior probability distributions in the BN (tan, unshaded boxes in Figure 5). Each of the nodes contain probabilities for the node states expressed as percentages and with corresponding belief bars; 'beliefs' represent the probability a node is in a particular state.

We now demonstrate how a BN can be used for inferences. The probabilities and the model are hypothetical and no ecological inferences are intended. Predictions for potential outcomes from implementing a primary sewage treatment program can be made with a specified BN (Figure 5a). The reef state is more likely to be dominated by algae (77%) than by coral (23%) under this program because of untreated nutrients reaching the reef. In this scenario, high species diversity appears slightly favored over moderate and low diversity. However, the relatively flat distribution across the possible outcomes indicates considerable ignorance on species diversity for the primary treatment scenario. Dive satisfaction also appears to have relatively high uncertainty about the likely outcome state but low satisfaction is the most probable. Looking across the network's predictions from primary

treatment (Figure 5a) to secondary sewage treatment (Figure 5b) and finally to tertiary sewage treatment (Figure 5c), nutrient loadings are less likely to be high, reef state is more likely to be dominated by coral, high species diversity becomes more likely, and dive satisfaction is more likely to be high. This example could be extended by an economic value node for dive satisfaction. If additional benefits were expected, the value of each could be examined for trade-offs and compared under different management scenarios. For example, the coral diversity resulting from lowered nutrient loadings might not support as well the reef building species that bring about greater wave attenuation and property protection. Analytically, each ES can be evaluated in natural units before economic and stakeholder valuation of trade-off scenarios.

Evidence collected in a monitoring program can be used to update the likely state of unobserved variables in the parent nodes. This same example can be used to demonstrate how new evidence updates beliefs about unobserved variables. Assume again that primary treatment is implemented at the wastewater plant, but a new monitoring program provides evidence that the reef is dominated by coral and species diversity is high. This new information can be used to re-evaluate the predictions of our initial BN (Figure 5(a)) into a revised model (Figure 6), where the distributions for other variables can be calculated, including coastal nutrient loadings. With the inclusion of hard evidence, we find that nutrient loadings to the bay are less likely to be high compared to our initial predictions where only the sewage treatment type was considered (Figure 5(a)). Furthermore, dive satisfaction now has a 98% posterior probability of being high. In other words, initial beliefs about the influence of primary sewage treatment on satisfactory dive experiences were updated from observations made on ES outcomes.

3.3. Simulating Changes in the Economic Value for a Coral Reef System over Time

Dynamic BNs extend the static representation of traditional BNs and depict changes in uncertainty over time. Their application in scenario analysis of economic value or ES provision can be useful for models constructed using BNs, or other approaches. Essentially, a dynamic network creates multiple instances of variables at each time step of interest. If functions between variables remain constant between time steps, analyses have fewer quantitative requirements. This is demonstrated with a case study adapted from the scenario analysis of a total economic value assessment of U.S. Virgin Islands (USVI) coral reefs (van Beukering et al. 2011). The scenario analysis examines how a dynamic BN can provide insights on the implications of future changes to total economic value estimates. The BN provides a powerful visualization and calculation tool for temporal uncertainties in ES economic scenarios. The networks for this section were executed in Bayesialab 7.0.1 (Bayesia S.A.S. 2017).

Three temporal scenarios were examined in van Beukering et al. (2011). The scenarios were multipliers of the economic value calculated for USVI coral reefs on an annual basis with no changes for the baseline scenario, a 2% annual decrease for the degradation scenario, and a 1% increase for the recovery scenario.

Using data from van Beukering et al. (2011), the upper and lower bounds (98.9–273.2 million \$/yr) placed on the economic value estimates were used to construct a triangular

distribution with 202.1 million \$/yr (the average, interpreted to be the mean for this example) used to calculate the mode (peak) of the distribution. The scenario analysis in van Beukering et al. (2011) relied exclusively on the average value but the BN will be used to accommodate the additional information and uncertainties on the range of potential outcomes. The estimated lower bound of the economic value of ecosystem services for USVI coral reefs approached \$100 million (van Beukering et al. 2011). This value will be monitored in the scenarios to examine the sensitivity of sinking below a lower bound estimate of economic value for coral reefs in USVI. For simplicity, we assume a zero percent discount rate for present value estimates in this exercise, although the impacts on uncertainties from different discount rates could be incorporated as an extension.

A simple three-node BN showing the scenario modeled in van Beukering et al. (2011) was developed (Figure 7(a)). Here the probability of coral reef economic values can be examined without the influence of parent nodes on the distribution of potential scenario occurrences. The second structure in Figure 7(b) extends this further by incorporating hypothetical scenario uncertainty arising from management interventions, which are displayed in the inset conditional probability table. The two hypothetical interventions represent a portfolio of options for management in the marine zone (e.g., establishing no discharge zones for recreational boats) and watersheds (e.g., establishing new voluntary practices for sugarcane farms). Their implementation can impact the probability of a recovery, degradation, or baseline scenario occurrence, and in turn, the probabilities of the annual value estimates for the coral reef system.

Probabilities for the estimated economic values of USVI coral reefs under three hypothetical scenarios, at the end of 25 years, are shown in Figure 8. The scenario multiplier was applied once for each year between 1 and 25. The corresponding annual probabilities for economic values were updated for each annual time period (AV_t) until year 25 was reached. The baseline scenario ends with the same mean value at year 25 as year 0 (202 million \$/yr). The other two scenarios predict a mean value ranging from 127 to 261 million \$/yr from USVI coral reefs. The lower and upper possible ranges are also different for each scenario, with greater values being more probable for the recovery scenario and lower values being more probable for the degradation scenario.

Also of interest are the likely management efforts required to achieve each scenario as calculated with the network in Figure 7(b) through diagnostic application of Bayes' rule. As expected, degradation is most likely associated with low marine and watershed management implementation, whereas the opposite is true for the recovery scenario. Baseline projections are associated with high marine management slightly more than high watershed management efforts. Forwards inference is useful for evaluating the outcomes from management options but backwards inference can be used to examine scenarios where desired or undesired outcomes on variables are observed to diagnose the level of management effort that was likely to have led to those observations.

The scenario analysis of annual average values performed by van Beukering et al. (2011) was duplicated here, but we incorporated the influence of uncertainties from management interventions and economic value estimates. Graphs of changes in annual average (mean)

values (Figure 9(a)) followed the example of Figure 9.3 in van Beukering et al. (2011), but we incorporated a distribution of economic values for each year into the annual estimates. The graphs with white-filled points follow the changes in the probability distributions for coral reef economic values when there is no scenario uncertainty (100% probability for each scenario), such as the ones in Figure 8. Trend lines with black-filled points represent various watershed and marine management interventions (100% probability for each intervention type) and the associated uncertainties for the future scenarios from applying the network in Figure 7b. Each of the BNs used to construct the lines give outputs that are largely below what is predicted for the baseline scenario, except for the recovery scenario and the scenario with high watershed and high marine management implementation. In this example, low watershed and high marine management more closely follow the baseline scenario than high watershed and low marine management, although both begin to diverge from baseline over time, due to greater losses in estimated economic value. This indicates that degradation is likely to occur if high management efforts are not implemented for both watershed and marine regions and the degradation is more likely to occur with low marine management efforts. Projected values under the recovery and degradation scenarios, without scenario uncertainty, enclose the upper and lower boundaries, respectively, for values resulting from all hypothetical management implementation scenarios due to the additional uncertainties in the latter.

One of the benefits of using the BN over a purely deterministic scenario analysis, is the ability to track key thresholds and targets in economic estimates. In Figure 9(b) this is illustrated for our previously designated threshold of \$100 million/yr. Over the time period of concern, all of the scenarios produce relatively similar annual probabilities for equaling or falling below \$100 million/yr, except for the degradation, and low watershed/low marine management scenarios, where probabilities for equaling or falling below the threshold increase in an exponential fashion from year 0 to year 25.

Management scenarios analyzed with consistent changes across time steps for the purpose of sensitivity analysis are insightful for examining potential implications of changes in the economic value of the reefs, but should incorporate additional information that would increase predictive power (van Beukering et al. 2011). A simple BN structure can be quite useful for predictive purposes if built on realistic estimates and quantities. However, the dynamic BNs in this section would require further elaboration as to the mechanisms and uncertainties from intervening on a coral system and changes to economic values. Also, focusing exclusively on annual values should be done with caution and incorporate possible phase shift relationships from episodic events (Sidle et al. 2013) such as bleaching from sea surface temperature events or adverse effects of ocean acidification. Dynamic networks can be extended to evaluate potential phase shifts along with interventions to build resilience in coral reef condition and, in turn, on economic value estimates.

3.4 Assessing the Impacts of Episodic Events on Ecosystem Services

Episodic events can confound predictions based on expectations of constant recovery or degradation of resources. The schematic of Figure 1 can be useful in a coral reef model that better considers the implications of management interventions on coral reef ES that face

episodic stressors over time. Figure 10 shows the flow of such a model with watershed interventions to establish and encourage best management practices (BMPs) in the agricultural zone. Boxes in Figure 10 (e.g., coastal water quality) would not be nodes themselves, but sub-models containing multiple nodes that interact with one another and potential nodes in other sub-models. Ultimately, benefits and costs accrue in the marine and watershed zone from the accumulated interventions and stresses over time. Interventions result in changes to nonpoint pollution discharge to the coastal zone and reef system. This influences water quality, which in turn influences the condition of the reefs at time 0. The appearance of a heatwave on the reef system, an episodic stressor event, changes future reef condition. A final time (t_2) is represented to examine recovery given the change to the reef system and the coastal water quality from the BMPs. Each time period examines the probability distribution for reef economic values resulting from reef condition and its uncertainties. After identifying the sub-models for Figure 10, we used nodes from existing coral reef BNs in the literature (cited in Table 2) to identify potential components for each of the sub-models.

4. Conclusions

This article provides context and situational examples highlighting the potential benefits of incorporating BNs into coral reef ES assessments. Frameworks and modeling procedures for assessing coral reef ES were combined with BN development and inferential capabilities to demonstrate how a BN modeling process can support ES conceptual and quantitative assessments that lack certainty. A BN approach can be integrated with socioeconomic and natural science research that supports policy decisions and evaluates ES outcomes. A decision analysis framework, coupled with BNs, not only complements more traditional means of ES assessment, but also can help differentiate between impacts to final and intermediate ES. Since the publication of the Millennium Ecosystem Assessment in 2005 (MEA 2005), ES benefits have been vigorously explored, hypothesized and debated. Probabilistic thinking can assist analysts in properly defining ES for assessments and considering the uncertainties in their knowledge of ES relationships and outcomes. Developing BNs allows decision-makers to incorporate knowledge or data that characterizes the likelihood of achieving satisfactory or unsatisfactory outcomes. While this study has focused on the potential application to ES within coral reefs, the methods are likely transferable to other natural resources, as all ES assessments will encounter uncertainty in available information.

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Figure 1.
A causal schema for Bayesian network components in ecosystem service assessments
(modified from van Beukering and Cesar (2004) and NRC (2005)).

Figure 2.

Example of a Bayesian network for an ecosystem service problem involving the hypothetical impacts of future ocean acidification on coral surface area and coral surface area on fishing stock at (a) the level of relation, (b) the level of function, and (c) the level of number. H = a high state for the variable, L = a low state for the variable, CPT = conditional probability table, OA = ocean acidification, CSA = coral surface area.

A) Property Protection

B) Recreational Opportunities

C) Fish for fisheries

D) Biochemical metabolites for commercial products

E) Existence value

Figure 3.

Conceptual models for constructing Bayesian networks to assess selected coral reef final ecosystem services derived from production function methods. Solid lines represent relationships explicitly defined by calculations of ecosystem services production through models or composite indices (see Yee et al. 2014); dashed lines indicate additional potential relationships according to our own judgment among variables (e.g., correlated).

Figure 4.

Possible integrated model combining conceptual Bayesian networks from Figure 3 for coastal property protection, recreational opportunities, bio-chemical metabolites for products, and commercial fish production for fisheries (in bold). Solid lines represent relationships explicitly defined by calculations of ecosystem services production through models or composite indices (see Yee et al. 2014); dashed lines indicate additional potential relationships among variables (e.g., correlated), according to our own judgment.

Figure 5.

Bayesian network example examining the influence of sewage treatment types on recreational dive experiences, including (a) primary treatment, (b) secondary treatment, and (c) tertiary treatment. Gray nodes indicate that new evidence has been entered into the node's state(s) (e.g., 100% probability of primary sewage treatment).

Figure 6.

Bayesian network displaying probability distributions for dive satisfaction and nutrient loadings given that primary sewage treatment is implemented, the reef state is observed to be dominated by coral, and species diversity is high. Gray nodes indicate that new evidence has been entered into the node's state(s) (e.g., 100% probability of primary sewage treatment).

Figure 7.

Dynamic Bayesian network structures for examining changes to the economic value estimates for U.S. Virgin Islands coral reefs, adapted from van Beukering et al. (2011); (a) initial simple dynamic network representing the impact of the present annual value (AV₀) and a deterministic scenario choice on future values (time t) of ecosystem services of coral reefs; (b) extension of the scenario in (a) to represent the impacts of marine and watershed management alternatives on the probability of a recovery, degradation, or baseline scenario. The hypothetical conditional probability table is for the scenario node in (b), representing the probability of a baseline, degradation or recovery outcome based on high or low levels of management. The dashed arc refers to a relationship that extends over additional time steps, AV= annual value.

Year 25
Degradation

Year 25
Baseline

Year 25
Recovery

Figure 8.

Example scenarios for examining the uncertainty of coral reef annual value (AV) of ecosystem services in the U.S. Virgin Islands from the models in Figure 7. The percent probability is shown on the left and the annual value (AV) on the right of the graphs. The three distributions are the AV probabilities for each scenario at Year 25 under three different scenarios (recovery, baseline, and degradation). For comparison, the probabilities of low or high watershed or marine management regimes from Figure 7(b) are presented for each scenario.

Figure 9.

Scenario analysis of U.S. Virgin Islands (USVI) coral reefs' economic value (million \$/yr) under three scenarios with and without scenario uncertainty; (a) Annual average economic value estimates for USVI coral reefs, (b) percent probability that annual values fail to exceed 100 million \$/yr. WS=watershed, Mar= marine, AV=annual economic value.

Figure 10.

Example Bayesian network schematic for examining the influence of best management practice (BMP) implementation on economic value of a coral reef over three time periods. The rounded boxes represent sub-model objects encompassing multiple variables and their relationships for each labeled category. $T \neq$ time period i .

Table 1

Bayesian network idioms that can be used for inferences in ecosystem service assessments.

Idiom	Use in a Bayesian network	Example use in a coral reef ecosystem service assessment
Definitional/synthesis	Condense multiple variables into one variable to simplify a model or to define a new variable	Coral condition defined by species composition, coral abundance, physical status, and biological condition
Measurement	Represent the uncertainty of the true state of a variable from measurement inaccuracies	Represent the uncertainty of the true fishing intensity of a fleet through a proxy measure such as number of ships or active licenses
Induction	Forecast the future state of a variable from past observations	Use historical observations of recreational visits at a site to predict future recreational visits at a site
Reconciliation	Reconcile predictions from different model output	Use both the distance of a reef to seagrass and a definition of habitat quality from rugosity and coral cover to examine fish habitat quality
Cause-consequence	Examine the uncertainty in a causal relationship between variables	Assess impacts on coral condition from ocean acidification which in turn causes impacts on the fishing stock from a reef (see Figure 2)

Table 2

Literature examples of Bayesian network nodes and sources with potential for estimating probabilities for examining the resilience of coral reef ecosystem services to episodic heat stress. Objects that encase nodes are shown in Figure 10.

Object	Example nodes	Conditional probability table derivation	References
Best management practices (BMP) implementation	Intervention nodes pertaining to BMP introduction in the agricultural region, BMP adoption rate and timing, agricultural practices, cropping technique, land use, fallow management, tillage, fertilizer applications, production costs, crop yield, income	Deterministic decision node input to agricultural system, surveys of growers for adoption rate and practices, production systems model, agro-economic cost-benefit model	Shenton et al. 2010; Thomas et al. 2009, 2012
Agricultural/ watershed runoff	Soil type, nitrate/sediment runoff, nutrient/sediment loading, riparian vegetation condition, dissolved inorganic nitrogen (DIN) transport efficiency, nitrate/sediment trapping, river flow/discharge, wetland condition, denitrification efficiency, DIN concentration at river mouth	Expert opinion, biological survey data, field monitoring data, discharge monitoring, soil experimental data, denitrification loss studies, erosion model, hydrodynamic model	Franco et al. 2016; Shenton et al. 2010; Thomas et al. 2009, 2012
Coastal water quality	Water quality change, water clarity, turbidity/ light attenuation/availability, pH, aragonite saturation state, nutrient availability/limitation, phytoplankton biomass, reef nutrient exposure	Expert opinion, monitoring data, published studies, coastal circulation/ hydrodynamic model simulations	Ban et al. 2014; Fletcher et al. 2014; Franco et al. 2016; Renken & Mumby 2009; Shenton et al. 2010; Thomas et al. 2009, 2012
Coral reef condition	Hard coral cover, larval supply, settlement, coral recruitment, reef rugosity, structural complexity, symbiont density, pigmentation, bleaching, disease, coral mortality, coral recovery, recently killed corals, crown-of-thorns outbreak, sea urchin density, bivalve density, sponge density, carbonate production, calcification, macroalgae cover, parrotfish density, herbivore/ piscivore/ carnivore abundance/ biomass/ density, herbivory, grazing pressure	Expert opinion, field/ site biological monitoring data, experimental data, published studies, survival analysis functions	Ban et al. 2014; Franco et al. 2016; Leenhardt et al. 2017; Renken & Mumby 2009
Coral reef economic value	Aesthetics, quality of reef experience, tourist return rate, tourism growth, tourism demand, fisheries landed value, fish abundance, income, revenue, total utility	Expert judgment, monitoring data, tourist survey data, visitation data, linear and nonlinear rule-based estimates, simulation modeling	Fletcher et al. 2014; Gilby et al. 2016; Thomas et al. 2009, 2012; Varkey et al. 2013
Ocean heatwave	Summer sea surface temperature, thermal history, heat stress, deeper water upwelling/ mixing, heat stress amelioration	Remote sensing data, simulation modeling	Wooldridge & Done, 2004; Wooldridge et al. 2017