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Research Article

A Bayesian Belief Network for assessing ecosystem services and socio-economic development in threatened estuarine regions

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Abstract

Estuaries feature diverse ecosystems with great biological production and favourable resources and landscapes for ecotourism. Increasing natural disasters have threatened the lives and safety of over 70% of the region's population in recent years. Rapid urbanisation and tourism have changed land use. This changes ecosystem structure and function, impacting service provision. This study developed a Bayesian Belief Network (BBN) model to assess the imbalance between socio-economic development and resource conservation using an ecosystem services (ES) approach. The BBN model helps synthesise and exchange information, provide decision-making data, evaluate trade-off possibilities and anticipate future situations when assessing ES. The BBN network model probabilistically evaluates ecosystem services using expertise, statistical modelling, geographic information systems and interviews. We assessed the comprehensive value of 17 forms of ES for four ecosystem groups over a period of 30 years. As a result, the cultural ecosystem services of some estuarial regions in Vietnam have the highest value and are showing an increasing trend, while the regulating ecosystem services are continuously fluctuating and decreasing. Provisioning ecosystem services are stable with small changes. This study also examined

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ES values in six landscape categories and created two ES change scenarios. The findings can help managers choose land-use and resource exploitation policies, understand the value of ecosystem services at the regional level and develop estuary sustainability strategies for long-term ecosystem service balance.

Keywords

land Use, sustainable development, estuary, tourism, urbanisation, scenario

Introduction

Estuaries are semi-enclosed bodies of water where freshwater from rivers and a coastal stream merges with the ocean (Sun et al. 2012), form multiple unique habitats that support highly diverse communities and provide crucial links to nearby ecosystems (McLusky and Elliott 2004). Ecosystems provide important services for human well-being, health and livelihoods (provisioning, cultural, regulating and supporting services) (Ruskule et al. 2018a, Assessment 2005, UK 2011), such as aquatic resources, natural hazard prevention, tourism values and specific cultures. The estuary area is a densely populated area in the world, accounting for approximately 60% of the global population concentration (Kennish 2002, Small and Cohen 2004), with urban areas, human economic activities and national defence and security. Of the 32 largest cities in the world, 22 are located in estuary regions. Ecosystems provide important services for human well-being, health and livelihoods (Ruskule et al. 2018, Reid et al. 2005, Government 2011), such as aquatic resources, natural hazard prevention, tourism values and specific cultures. The total economic value of estuaries is very large, estimated at 4.1 trillion USD and rising to 6.1 trillion USD in 2014 (Costanza et al. 1997). The estuary region's resources create conditions for urban expansion and tourism development. The World Bank projects coastal tourism as the leading economic sector by 2030 (Manzoor et al. 2019), contributing approximately 20% of the global GDP (Nguyen et al. 2020).

However, estuaries are a dynamic and complex adaptive system (Parry et al. 2007), a sensitive area facing high pressures and disaster risks (Allen et al. 1999). Estuaries are most severely threatened ecologically (Salm and Clark 2000), especially due to climate change (Wong et al. 2014, Oppenheimer et al. 2022, Coppola et al. 2023), leading to changes in the structure and function of ecosystems (Leal Filho et al. 2022, Kara 2019), and a reduced ability to provide goods and services to society (Alexander 1999, Foley et al. 2005). The process of rapid urbanisation and economic development leads to conflicts over resource use and environmental degradation (Thia-Eng 1993, G.ossling 2002) and land-use loss (Nitivattananon and Srinonil 2019, Vitousek et al. 1997). According to the Organisation for Economic Cooperation and Development, the number of people in 136 major port cities suffering from storm surges may increase from 40 million (2005) to 150 million (2070), with losses ranging from 3 trillion USD to 35 trillion USD (Nicholls et al. 2008). Economic losses due to extreme weather events double every 12 years at a rate of 6% annually in developing countries (UNEP 2006). The natural

ecosystems in the estuary region are the most used and threatened worldwide: 50% of salt marshes, 35% of mangroves and 29% of seagrass have been lost or degraded due to human activities (Barbier 2017). The decline of global estuarine and coastal ecosystems has reduced the ability to self-recover by 33%, the ability to provide habitat for organisms by 69% and the ability to provide filtration and detoxification services from vegetation and wetlands by 63% (Barbier et al. 2011). Therefore, assessing ecosystem service (ES) is essential in current studies for the rational management and planning of natural resources. This approach can provide a potential tool to assess the overall impact on people and confront the challenges of climate change.

Various methods have been used to evaluate ES of estuaries, such as economic evaluation (Lee and Du Preez 2015, MacDonald et al. 1998, Pinto et al. 2010), ES mapping (Burkhard et al. 2012, Nguyễn 2020, Stürck et al. 2014) etc. Economic valuation studies focus on traditional groups, such as market prices and tourism costs. However, the translation of ecosystem service valuation into appropriate financial mechanisms has not yet been fully resolved, such as the economic value for aesthetics or ecological benefits (Hufnagel et al. 2018). ES assessment models and ES mapping tools are used, such as InVEST, ARIES, SWAT etc. The InVEST model can be run at different spatial scales and extents, but spatial relationships amongst landscape components are oversimplified in the models (Nemec and Raudsepp-Hearne 2012). The ARIES model required substantially more time and expertise to assess independent ecosystem service models (Waage 2014).

Meanwhile, the Bayesian Belief Network (BBN) can be used in parallel with mathematical models, providing different functions (Landuyt et al. 2013) such as predicting, senario development and mapping. Based on the capacity matrix approach (Burkhard et al. 2009, Burkhard et al. 2012), BBN allows assessment of both ecological and ecosystem services in a table matrix (Campagne et al. 2017, Campagne and Roche 2018) and assessment of a higher number of ES than other methods (Nemec and Raudsepp-Hearne 2012). The BBN has become a popular ES assessment technique (Jacobs et al. 2015) and a useful tool for decision-makers and environmental managers (Swetnam et al. 2011). The BBN model has been applied to the assessment of ES, mapping and building future scenarios through the development of a matrix table approach (Landuyt et al. 2013, Burkhard et al. 2012). Assessment of ES and scenario development for a developing country like Vietnam is necessary, especially when natural disasters are becoming more intense and the poor resilience capacity makes the level of damage more severe.

The objective of this study is to apply the BBN model to assess the ecosystem service value of 04 ecosystem groups and show the relationship between ecosystems and their ES by the process urbanisation and tourism development. Information about socio-economic aspects and land-use status in the study was collected from fieldwork, interviews and multi-source remote sensing - GIS data. Scenarios, based on land use changes, were generated, based on the model to have an objective view of the trade-offs between ES. The results regarding changes in land use/land cover and the value of ES and scenario through the BBN model approach are explained in the Discussion. The outcomes of this study can contribute to the decision-making process and policy development in the rational use and conservation of estuarine ecosystems.

Material and methods

Case study

We chose the estuaries in Quang Ninh and Quang Nam Provinces to build BBN models. The selected areas contain typical inland and wetlands ecosystems to a depth of - 6 m. The estuary region of Quang Ninh Province has four large estuaries: Bach Dang, Ka Long, Tien Yen and Ba Che (Fig. 1). The estuary region in Quang Ninh Province has the Nature Reserve - Dong Rui Wetland with 400 species of fish and 140 species of seaweed (Hà 2022). Economic and cultural activities, industrial parks, coastal urban areas of the Province are concentrated in estuaries and coastal areas. The number of tourists in 2019 reached 4.4 million and fee collection reached more than 1,294 billion VND (50.8 million USD) (Lịch 2020). Total output of exploited and aquaculture seafood in 2021 will reach 149,890 tonnes, reaching 13,009.59 billion VND (512.7 million USD), accounting for 52.5% of the value of the entire industry (Hà 2021). However, the ecological environment faces many problems from the increased sedimentation entering the port. It has narrowed the distribution area of estuarial ecosystems from 1990 to 2008, such as mangrove forests by 7,253 hectares (or 25%), tidal flats by about 10,425 hectares (or 21%) and seagrass beds by 650 hectares (or over 80%) (Lan et al. 2013). The main causes of the decline come from the intensive farming of aquaculture and salt levelling and the increase in storms and floods. Coal-mining activities impact the average sedimentation rate in coastal areas, accounting for about 12.5% of the total sedimentation value (Vinh et al. 2012).

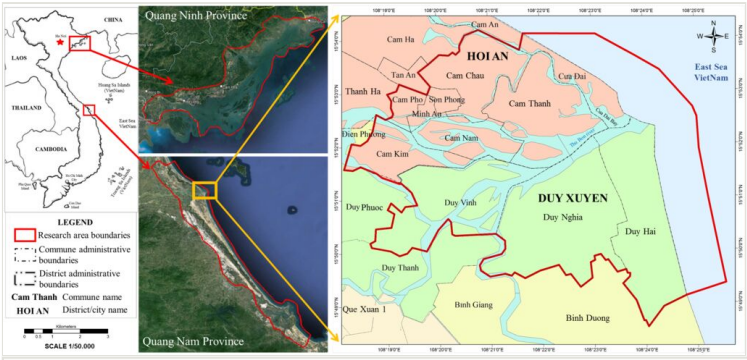

Figure 1.

The location of two chosen large estuaries for ecosystem service assessment in Vietnam. The figure clearly demonstrates the rapid and clear expansion of the urban area from 1985 to present.

In Quang Nam Province, there are two large estuaries, including Thu Bon Estuary and Truong Giang River Estuary (Fig. 1). With low-lying terrain, coastal cities in Quang Nam, including Hoi An, Vinh Dien, Tam Ky, Nui Thanh and Tam Hoa face many challenges from river and sea bank erosion and flooding. More than 3,000 houses in Tam Ky experienced deep flooding at the end of 2021. However, the estuary area of Quang Nam Province has a long coastline with many beautiful beaches for the service industry. In 2019, the total

number of visitors and stays reached more than 7.8 million and income reached 14,570 billion VND.

The Thu Bon Estuary is the downstream area of the river that flows into the East Sea at Cua Dai and is the key economic region of the country. The mangrove coconut forest ecosystem not only has cultural and historical value, but also provides a favourable environment for the livelihood and development of various aquatic species. The nucleus of Hoi An urban centre, the Old Town, which has an area of 5 km^2, has been recognised by UNESCO as a World Cultural Heritage Site (4/12/1999). The Cu Lao Cham-Hoi An Biosphere Reserve identified the Thu Bon Estuary as its buffer zone in 2009. The process of urbanisation and coastal tourism development has taken place rapidly, making it challenging to control emerging problems. From 2004 to 2016, approximately 112.5 hectares of some wetland ecosystems in the Biosphere Reserve were lost, including 77.1 hectares of mangrove forests, 34.6 hectares of seagrass beds and 0.8 hectares of coral reefs (Nguyen Van and Tong Phuoc 2021). The conversion of land-use purposes and the construction of infrastructure put pressure on conservation efforts, degrading natural ecosystems. Many animals and plants lost their habitats, disrupting the integrity of estuarine ecosystems and reducing the supply of ES.

In the Thu Bon Estuary area, six main landscape types have been identified, including:

1. River - swamp landscape;
2. Sea - wind landscape;
3. Sand-dune landscape;
4. Shallow water landscape (0-5 m depth);
5. Deep water landscape (5-30 m depth);
6. Alluvial landscape.

Alluvial, shallow water and deep water landscapes include the ecosystem of the upper surface water and underlying marine life ecosystems (aquaculture, seagrass and coral reef). In addition, sandy dunes appeared in the “shallow water landscape” in the north of the Thu Bon River in the years 1992-1997 and in recent years, in the “deep water landscape” where the river discharges into the sea. In the “alluvial landscape”, aquaculture structures for seafood farming established by residents are forming gradually at the old riverbed. The “river - swamp landscape” encompasses the most comprehensive range of ecosystems considered, such as residential areas, agricultural areas, bare land, aquaculture (mainly intensive farming) and mangrove coconut forests. Notably, the gradually expanding residential areas rank second in size after agricultural land (rice paddies and grasslands), followed by the forest ecosystem. The “sand-dune landscape” concentrates in residential areas, coastal tourism and construction works in the north of the Thu Bon Estuary and protective forests and rural and agricultural communities in the south of the Estuary. This landscape has a stretch of sandy beaches directly affected by the waves. The “sea - wind landscape”, accounts for most of the area of agricultural land and human settlement land. Land with sparse vegetation, bare land cover a small area. There are aquaculture ecosystems whose water surface is not large, occupying less than 5% of the total area.

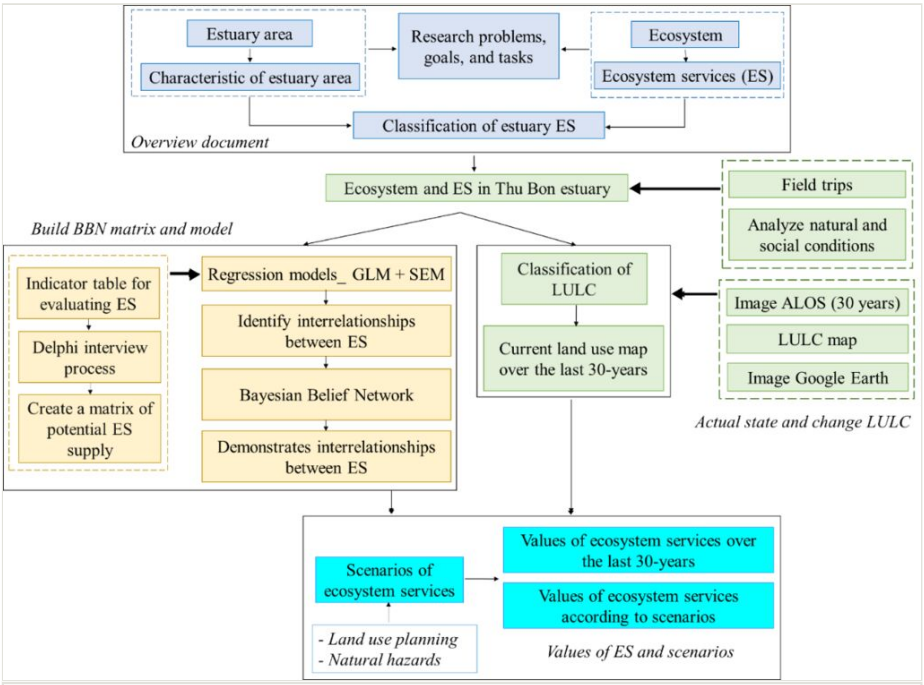

Figure 2.

The contents of the study to assess estuarial ecosystem services.

Methodology

To assess estuarial ecosystem services, based on the BBN model, the study processed four steps: the first was an overview of documents and fieldwork to identify estuary ecosystems and related ES (presented in the Introduction). In the second step, the ecosystems of estuary area can be extracted from LULC maps (in the "Database for model development" and Fig. 3). An ES matrix table was developed, based on expert knowledge, then put into the regression model include GLM (Generalised Linear Model), SEM (Structural Equation Model) (Fan et al. 2016) to calculate the relationships between ES in the third step (Fig. 4). The results of the matrix table are summarised in Table 1. The links and data were transferred to the BBN model before applying to particular regions. The results of the study at step three are presented in "Statistical analysis of interdependence as a basis for BBN parameterisation" and displayed in Appendix 2. In the fourth step, semi-quantitative values of ES were calculated, based on a developed BBN model during the last 30 years and for the scenarios of regional planning and natural hazards up until 2030. The analysis of the data calculated by the model compared to reality is in "Value of ecosystem services in the Thu Bon estuary area" and "Scenario results". The "Development of the BBN Model" is described in detail in steps 2 to 4. Fig. 2 clearly illustrates these steps:

Table 1.

Matrix to evaluate the potential to provide ecosystem services (ES) of different estuarial ecosystems in Quang Ninh and Quang Nam Provinces, Vietnam

Group	LULC	Residential ecosystem					Agricultural ecosystem		Forest		Wetland ecosystem						
		ODT	KDL	CDG	ONT	BCS	DCS	LUC	RPT	LNK	NTS	SON	A1	A2	A3	B1	B3
Provisioning	Crops	30	5	5	50	5	40	90	5	5	10	5	5	5	5	5	5
	Livestock	20	5	5	40	20	80	5	10	10	5	5	5	5	5	5	5
	Timber	10	5	10	20	5	5	5	5	10	5	5	5	5	10	5	5
	Fish and other Seafood	5	5	5	10	5	5	5	5	5	90	40	5	5	20	60	90
	Minerals	5	5	5	5	5	5	5	5	5	5	30	10	10	10	5	5
Regulating	Groundwater recharge	10	10	10	10	10	50	50	90	70	30	90	10	10	60	10	5
	Local climate regulation	20	10	5	30	10	40	40	90	90	30	60	5	5	30	40	70
	Global climate regulation	20	10	10	30	5	60	40	90	90	20	30	20	20	30	50	40
	Air quality regulation	10	10	5	30	20	20	20	90	80	10	10	5	5	10	5	5
	Flood regulation	20	10	5	40	10	40	30	90	70	10	50	30	20	50	30	40
	Erosion regulation, water	20	20	10	10	5	20	20	90	70	5	20	20	5	5	5	5
Cultural	Recreation and tourism	50	90	5	50	5	30	40	90	20	50	80	90	60	40	50	70
	Landscape aesthetics	50	80	5	40	5	30	50	80	20	40	90	70	70	70	50	50
	Knowledge systems	50	40	10	40	5	20	40	90	30	30	80	60	60	60	10	10
	Cultural heritage	80	40	10	60	5	50	70	70	10	40	80	70	20	20	10	10
	Regional identity	70	60	10	60	10	20	70	90	10	30	80	70	70	20	50	50
	Natural heritage	30	40	5	40	5	40	30	90	20	20	80	70	70	80	30	30

Table 2.

Changes of ecosystems and land use/cover in the two scenarios until 2030.

Ecosystems	Urbanisation and tourism development	Preservation of natural landscapes
Residential/Urban	Expand by +400 ha	Stabilise or Narrow -100 ha
Agricultural	Reduce by - 150 ha	Increase by + 50 ha

Ecosystems	Urbanisation and tourism development	Preservation of natural landscapes
Forest	Reduce by 40% (Equivalent to - 250 ha)	Increase by 20% (Equivalent to + 100 ha) mainly protection forest
Aquaculture	Expand by + 50 ha	Stabilise or reduce by - 50 ha
Beach	Narrow - 5 ha from the sea side	Expanded to the sea side + 5 ha (Cua Dai beach)
Water surface of river and sea	Narrow by - 50 ha	Remained stable

Table 3.

Changes of area in some types of LULC from 1991 to 2020 at Thu Bon Estuary (unit: ha).

LULC	1991	1995	2000	2005	2010	2015	20 20
Residential area	221.6	256.6	336.9	643.5	969.7	1,230.5	1,522.5
Agricultural	2,570.6	2,855.8	2,553.2	2,486.3	2,237.9	2,141.8	2,049.3
Other croplands	1,671.8	1,697.9	1,821.6	1,571.1	1,144.1	1,185.7	979.3
Bare soil	818.6	663.8	634.4	570.2	598.2	552.7	426.9
Forest	993.2	966.1	833.8	525.4	773.2	699.6	802.5
Aquaculture	110.6	208.1	301.9	541.2	757.7	806.1	750.0

Database for model development

The database used to develop the model involves the classification of ecosystems and land use/cover types which, in turn, helps to categorise their respective ES. Fieldwork at the estuaries, which took place in July 2022 and was combined with published sources (textbooks, articles and statistics), aimed to classify two main groups of ecosystems:

1. terrestrial ecosystems (agricultural, beach sands, dunes, floating beaches/islets and residential communities) and
2. wetland ecosystems (silt tide - sand, mangroves, aquaculture, seagrass and coastal sea).

The low-lying, wet and frequently inundated terrain of the wetland ecosystems presents a stark contrast to the upland areas, which exhibit high biodiversity values. In order to determine the spatial distribution of ecosystems/land use/cover, the study integrated multi-source remote sensing images, landscape maps and ecosystem maps in a 30-year assessment.

The research employed Worldview-2 image data obtained from Google Earth Pro to discern the various categories of overlays that have occurred in the Thu Bon Estuary over the past five years. The Advanced Land Observing Satellite (ALOS) data were utilised to identify overlays in the last thirty years. LULC data images were collected from the open data site*[1] obtained from Japan's ALOS satellite. The images had a spatial resolution of 30

m x 30 m. A random forest-based algorithm and numerous informative geospatial data sources, including Landsat and Sentinel 1 and 2 images, were utilised to compile this annual dataset for Vietnam. The research employs a second grade classification system comprising 18 categories to illustrate the complexity and variety of ecosystems with an accuracy range of 78% to 85%.

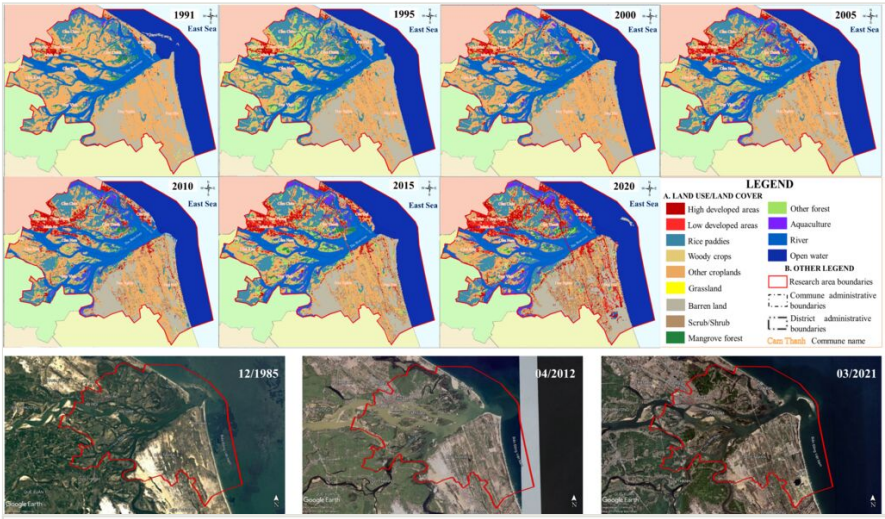

Figure 3.

Land uses/covers in the Thu Bon Estuary from 1991 to 2020.

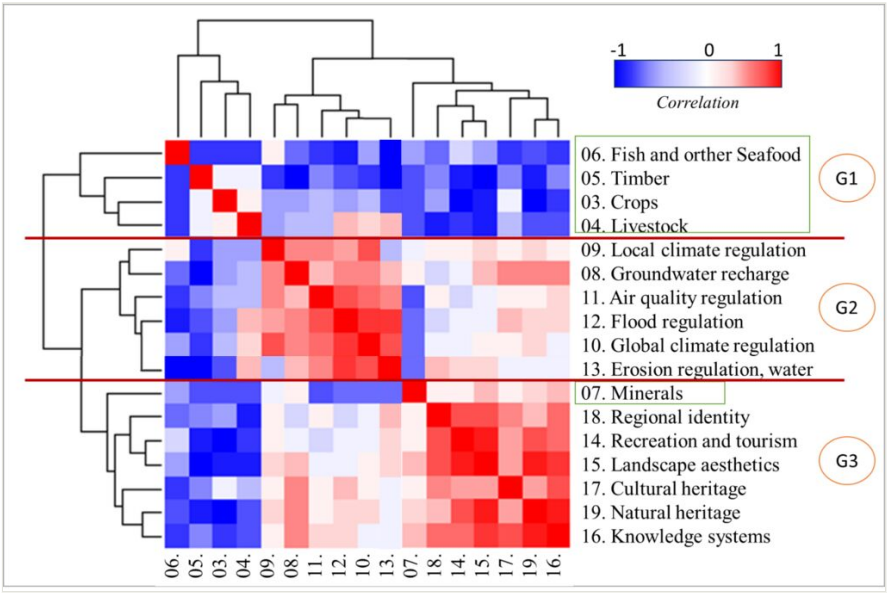

Figure 4.

The relationship between ecosystem services in the Thu Bon Estuary.

Development of the BBN Model

The BBN network is based on a probabilistic model approach, starting with artificial intelligence models, based on Bayes' theorem (Dang et al. 2021). BBN networks represent the cause-and-effect relationships of a system or dataset. The network consists of two important components: (1) directed acyclic graphs (DAGs) that denote the independence between variables; and (2) conditional probability tables (CPTs) that denote the strengths of the links in the graphs (Aguilera et al. 2011). The DAG consists of a structured set of variables or nodes that represent the modelled system. Nodes represent random variables with probabilities for a weighted cause and effect relationship. The edges are orientated from the parent node to the child node. Each node has a conditional probability status table based on the real values of the parent node. The resulting causal map forms the basis for developing an operational BBN. The Bayes' theorem can be formulated as:

$P(A|B) = \frac{P(B|A) * P(A)}{P(B)}$ (Dang et al. 2019),

in which "B" is the parent node (cause factor) and "A" is the child node (effect factor).

In the study on the application of the BBN model for the assessment of ES in estuary areas, the development of indicators for assessment is important. Indicators represent the content of the unit used to measure desirable characteristics (Hung and Hoe 2014). To assess the values of ecosystems, the selection of indicators must be convenient, suitable and easy to use in ES assessment. The study, which is based on the characteristics of the region, combined with Common International Classification of Ecosystem Services (CICES) Version 5.1, an ES classification system and synthesis of previous studies, selects 17 types of ES for three value groups: provisioning ES, regulating, ES and cultural ES. Subsequently, a matrix was constructed and the BBN model was established to identify the nodes in the network or ES types. The matrix was synthesised and implemented through the Delphi interview process (the indicators are presented in Appendix 1).

In Delphi interviews, evaluations from specialists are gathered and filtered through the use of questions that elicit repeated feedback. The concerns addressed in the table question pertain to the prospective availability of ES within each ecosystem. Every subsequent table question was formulated in light of the outcomes of the preceding table questions and the process was concluded when a substantial consensus was reached. Following consultation with twenty-one experts from universities and research institutes, the outcomes of the ES matrix table were implemented. Matrices containing information from expert groups in the domains of urban, agriculture, forestry, landscape, culture and ecology were distributed from the initial matrix. If scientists request experiments, complete matrices are also dispatched to them. They can modify or add to the land-use categories and coastal ES contains incorrect or missing types. Every modification suggested by the evaluator is consolidated into a composite matrix. The value is averaged if the difference between two values falls within the range of 20 to 40. The process then continues with the submission of the evaluation document and solicit feedback from the scientists in order to determine the final value if the discrepancy exceeds 40.

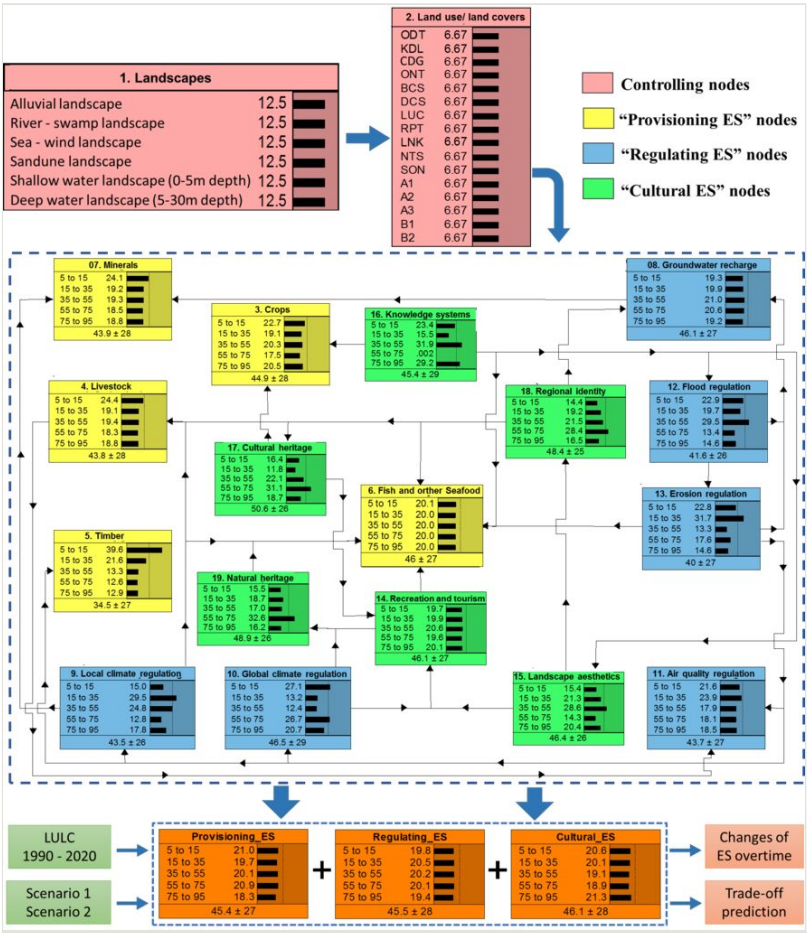

Figure 5.

Bayesian network to evaluate ecosystem services in the Thu Bon Estuary.

After consultation with scientists, the complete matrix included in the regression model SEM is integrated into the R programming language through Integrated Development Environment R-Studio 4.3 by packages "ggplot2", "hrbrthemes" "corrplot" and "PerformanceAnalytics/psych". A structural equation model (SEM) has been created to find suitable links between nodes (Illustration in Appendix 2). There are often BBN models that do not indicate the correlation between variables or which relationships are appropriate. Meanwhile, the SEM model clearly illustrates this issue. Therefore, building an SEM model is the foundation for connecting nodes inside BBN in a grassroots way. Furthermore, BBN connections will become more secure (Table 4).

The model illustrates the relationship between ES, showing how ecosystem services interact with each other (Fig. 4). Following these results, the BBN network was built with the application of Netica Application v. 7.01 (Netica Application is Bayesian network development software and trademarks of Norsys Software Corp). The model demonstrates

the connections between ecosystem services and calculates their values (Fig. 5). Then, the ES values of each ecosystem/LULC and the scenarios are calculated according to the formula:

$$\sum ES = \sum En * Lm ,$$

in which, “En” is the potential weight of the potential provision of ES “n” and “Lm” is the area of land use type “m”. The total ES value is equal to the sum of the service values taken into account. The results of the model are not expressed in measurement units because the input data are calculated in percentage proportions and then multiplied by five corresponding scale values (matrix table). This formula is applied to the values calculation in "Value of ecosystem services in the Thu Bon estuary area" and "Scenario results", combined with the matrix table weights 1.

Table 4.

An example about the sensivility of a “3. Crops” ecosystem service as a parent node to find at other nodes.

Node	Variance Reduction	Percent	Mutual Info	Percent	Variance of Beliefs
3. Crops	779.5	100	2.31655	100	0.6379132
17. Knowledge systems	7.847	1.01	0.01565	0.676	0.0011303
18. Cultural heritage	3.541	0.454	0.00940	0.406	0.0005951
16. Landscape aesthetics	1.693	0.217	0.00287	0.124	0.0001949
19. Regional Identity	1.354	0.174	0.00280	0.121	0.0001709
12. Flood regulation	0.2165	0.0278	0.00042	0.0181	0.0000277
15. Recreation and tourism	0.02879	0.00369	0.00005	0.00207	0.0000029
4. Livestock	0.01071	0.00137	0.00003	0.00109	0.0000014

Matrix for the assessment of the ability to provide ecosystem services of different ecosystem types in the estuary

In the matrix (Table 1), changes in the values of the variables are assessed over a long period of time. However, the study does not quantify values or apply quantitative methods. Therefore, the following indicators only indicate the ability (e.g. identifying the terms “high”, “medium” and “low”) without indicating specific values. This value is averaged over a long period of time, the value determined at least 30 years of study. This method supports the steps of quantifying factors affecting the formation process and providing related service groups. The ability to provide specific services of ecosystem types is assessed on a scale of 0-100, including five levels: Below 20 = no ability to provide ecosystem services; 30-40 = low supply capacity; 50-60 = average supply capacity; 70-80 = high supply capacity; over 90 = very high supply capacity. However, in reality, no ecosystem lacks the ability to provide services (= 0) or provide services maximally (= 100).

In which: ODT: Urban residential lands; ONT: Rural residental lands; KDL: Tourism lands; CDG: Construction sites, industry and commerce; BCS: Bare soil; DCS: Grasslands; LUC: Agricultural lands; LNK: Other perennial trees; RPT: Mangroves/Certified protection forest; NTS: Aquaculture lands; SON: Rivers and streams; A1: Embryo sandy dune; A2: Natural sandy beach ; A3: Alluvial lands; B1: Brackish water areas; B3: Deep sea waters (Appendix 5).

Scenario development

The development of scenarios is an essential function of the BBN model. As per the strategic plan of Hoi An City spanning the years 2020 to 2030, rice-growing land, natural forest land and forest land will be converted to non-agricultural purposes. The Provinces People's Committee in Quang Nam Province expects Hoi An City to become an exceptionally intelligent metropolis with a 40% urbanisation rate by 2030. Consequently, in accordance with the planning, the study formulates two scenarios: (1) Urbanisation and tourism development; and (2) Preservation of natural landscapes (Table 2). To assess the impact of future policies on ES, the two scenarios were constructed by reallocating the area ratio between different categories of LULC. The data were gathered in accordance with the Decree (province 2023a, province 2023b) of the Province of Quang Nam's general planning and the actual data were compared to the LULC area in 2020.

Scenario 1: “Urbanisation and tourism development” considers expanding settlements, tourism and investment in the direction of modernisation - industrialisation and rapid urbanisation. Some 400ha of housing area have been expanded due to the conversion of agricultural land, forest and bare soil. Agricultural land, annual crops and rice cultivation land were changed to aquaculture land. The scenario selected a forest area to be reduced by about 40% compared to 2020, equivalent to more than 250 ha. This area is partly a coastal forest for the construction of tourism areas, partly a forest around residential areas converted to housing land or other technical infrastructure development and the rest is due to the natural degradation of protection forests along mudflats. The water surface of rivers and seas narrows by 50 ha, mainly converted to coastal aquaculture; and this ecosystem is easily eroded every year at a high rate, so the area is narrowed.

Scenario 2: “Preservation of natural landscapes” focuses on the expansion of natural ecosystems, reducing pressure from socio-economic development. This scenario's main focus is to increase the regulating ES. The rating of the change in land-use types is at a stable level and towards the expansion of the protected forest ecosystem. The forest area expanded by 20%, equivalent to more than 100 ha. The focus is mainly on the coastal protection forests, coconut forests and other natural forests to help regulate storms and coastal erosion. Urban land or other infrastructure areas are stabilised or narrowed down to 100 ha compared to the urbanisation growth rate of the region (the urbanisation rate of Hoi An City is 74.5% (2021)). The beach area is expanded by 5 ha (especially the Cua Dai beach area) to help protect the inner coast area and attract tourism (Scenario results analysed in "Scenario results").

Results

Estuarial land use/cover changes

Fig. 3 illustrates the trend of changes in the Thu Bon Estuary, based on classification results from remote sensing images. In the early 1990s, the population was partly concentrated along the coast and on both sides of the Thu Bon River, serving marine livelihoods and partly concentrated in the old town area. By the 2020s, the population has concentrated more around the old town, expanding to the coastal strip for tourism development and forming small residential clusters in the other localities. Agricultural land for crops, such as rice and crops, has gradually stabilised with more organised planning compared to scattered distribution in many places. This type is concentrated in the floating areas of Duy Vinh and Cam Kim communes and the Cam Thanh area has also long had a large area of agricultural land (Table 3).

The coastline is experiencing significant erosion and landward shifts and tends to shift towards the south of the Estuary. For the downstream flow of the Thu Bon River: the river channel meanders, dividing into branches with numerous sandbanks, underwater areas and large and small mudflats on both banks, as in Cam Kim, Cam Nam and Duy Vinh communes. About 30 years ago, the river had many small branches and the process of conduction development was relatively “free”. After 30 years, some small flows disappeared and the main flows gradually grew larger. Large-scale erosion and accretion occur on both sides of the river. In the area of Hoi An ancient town, flow path fluctuations are related to the flow redirection on the main flow path, with many floating islands seemingly gradually “drifting” towards the estuary due to the combined impact of the river flow and tidal currents. Currently, people have gradually used these mudflats for settlement, cultivation and aquaculture purposes (Table 3).

The forest ecosystem/mangrove forests have developed steadily in the area of Cam Thanh, in river creeks. This ecosystem tends to change more continuously than other types of ecosystems. The most stable part is the Cam Thanh coconut forest area, which is currently under conservation. More stable is the forest ecosystem/protection forest distributed in Duy Hai and Duy Vinh communes, although the coverage is not high. The least modified type is barren/bare soils, which are mostly sandy soils difficult to cultivate and devoid of vegetation.

Statistical analysis of interdependence as a basis for BBN parameterisation

Co-relationship between estuarial ecosystem services

The provisioning ES is closely related to human activities and natural conditions such as soil characteristics, hydroclimate, fauna and flora systems, terrains (elevation and slope) and climate. Therefore, the distribution of ecosystems and their ability to provide ES vary

depending on spatial and temporal scales. Services within the same service group and between different groups always have mutual impacts.

Fig. 4 is built based on the expert weighted matrix data table (Table 1) with the help of a GLM model that provides correlations between ecosystem services (nodes). The GLM model serves as the foundation for building the SEM model. The GLM model evaluates the correlation between ecosystem services, but does not show the connection between them, so the GLM model is mentioned as a "reference model". Meanwhile, the SEM model shows the connection between nodes. From here, SEM will show the results for the BBN model and show the compatibility of the correlation between ecosystem services (Fig. 5).

Fig. 4 presents the matrix results, encoded with information and included in Integrated Development Environment R-Studio 4.3 by “corrplot” packages, illustrating the correlation between 17 types of ES (Appendix 1 provides a description of the 17 ecosystem services), with values ranging from - 1 to + 1. The redder the colour, the more positive the correlation. Conversely, the bluer the color, the more negative the correlation (increasing the value of one service will reduce the value of the other service) and 0 indicates no correlation.

This study divided the correlation into three groups (G1, G2, G3) with clear differences corresponding to provisioning ES, regulating ES and cultural ES. This division is based on the “branch/cluster” analysis to reflect the level of correlation between ES. In the three groups, the G2, G3 groups have more positive interdependence than the G1 group. The variables within a group also exhibit correlation with each other, particularly the cultural ES group, which demonstrates a very high correlation and the regulating ES groups, which complement each other. The provisioning ES group exhibits a very low correlation index, indicating a separation between the variables. The variables associated with G2 (No. 08-13) and G3 (No. 14-19) were strongly correlated (correlation coefficients from 0.7 to 0.9). The variables of cultural ES are positively linked to the following variables: local climate regulation and groundwater recharge and have a poorer link with three variables: air quality regulation, flood regulation and global climate regulation (Nos. 11, 12 and 10). The variables in the provisioning ES group (Nos. 03-06) tend to have mutually exclusive, negative correlations with all other variables in the matrix. The strongest negative correlation of the G1 group variables in the ecosystem is for the variables of cultural ES and less negative correlation with regulating ES. For example, the “Fish and other Seafood” and “Timber” variables have correlation coefficients from - 0.8 to - 0.9 and the “Crops” and “Livestock” variables have correlation coefficients from - 0.5 to - 0.8. The providing ecosystem services group a clearer demonstration of the fact that as one service develops, the other service declines.

The variable “minerals” (No. 07) exhibits different correlations compared to others providing ES, which is in the cultural ES group. Although the variable “mineral” is inversely correlated with other regulating and provisioning ES, it shows a more favourable, though not high, correlation with cultural ES variables, particularly with landscape and knowledge ones. (Nos. 15 and 16). The “mineral” variable includes both positive and clear inverse correlations compared to the other considered variables. For example, minerals have a high negative correlation value (- 0.7) with the “air quality regulation” variable and a lower

value (- 0.5) with the “flood regulation” and “global climate regulation” variables (Table 4). This means that the higher the weight of mining activities, the lower the weight of the regulating ES group. The process of sand exploitation in the riverbed causes a shortage of sedimentary streams, causing landslides on both sides of the river, air pollution, salinisation of coastal aquifers and groundwater reserves etc. Therefore, this correlation has a high index, but has a negative value.

BBN network in the assessment of estuary ecosystem services

It can be seen that the interdependence between estuarine ES is complex and determining parent and child nodes to develop BBN is very difficult. Table 2 and Fig. 4 link the number of these components to the ES matrix. The model eliminates poorer correlations, retains strong correlations and switches to a one-way connection (Fig. 5). (Appendix 3 and Table 4 explain how to implement and identify correlations). The “Landscape” and “Land use/cover” nodes (Nos. 01 and 02) are the root nodes to assess the current situation and change scenarios for each land use/cover type. The symbols in node 02 correspond to the LULC symbols in Table 1. The ecosystem service type nodes are intermediate parent nodes, consisting of nodes 03 to 19 (buttons in front of the arrow). The child nodes in the network are three nodes: "providing, "regulating" and "cultural". These nodes are affected by the parent nodes to generate the final value (the button behind the arrow) (Table 4). To show the connection between different types of ecosystem services, the SEM model calculates the connection ratio between nodes. For example, node 03. Crops have stronger correlations with nodes 17 and 18, as well as lower correlations with nodes 15 and 12. Therefore, inadequate correlations are excluded. This loop is performed for all nodes considered in the model.

In this study, the authors chose to evaluate LULC. Research on usage evolves continuously over time. However, managers do not seem to care about the appropriateness of land-use conversion. This makes urban development and tourism unreasonable. In addition, the study wants to evaluate the direct impacts of humans on each ecosystem for socio-economic activities, thereby leading to changes in the value of different types of ecosystem services.

Fig. 5 displays the percentages calculated at the time of data collection in 2023. Seventeen variables interacting with each other were analysed from the SEM model, demonstrating the trade-off in ecological service value when ecosystem area and land use/cover change. Therefore, 17 nodes are child nodes of parent nodes "Landscape" (No. 1) and "land use/cover" (No. 2). The probabilities shown at the child nodes in Fig. 5 will change when managers change the land-use planning policy. This change may have been noted in the past or planned for the future. After the percentage of land use/cover and ecosystem area changes, the new probability at the ES will be recalculated, based on the conditional property tables in each node. Thanks to mutual relationships between nodes, the probability of each node is controlled by linked nodes and the ratios between land use/cover and ecosystems. Once all probabilities are calculated, the total values of the three ES groups are also evaluated.

Through the linkage between the nodes in the model, it is found that the regulating ES nodes (8-13) are usually the original nodes, affecting the cultural ES nodes (Nos. 14-19) and the provisioning ES node (Nos. 03-07)). The nodes “provisioning ES” act as sub-nodes in the network, under the control of the other two ES groups. For example, node 6 “Fish and other seafood” is affected by six other ES types, including four cultural ES nodes (knowledge system, recreation and tourism, natural heritage and regional identity) and two regulating ES nodes (local climate regulation and erosion regulation). As the BBN model represents unique one-way relationships that do not maintain a bonding circle, a node may not directly influence all other nodes, but may impact them through intermediate nodes. For example, node 15 (landscape aesthetics) and node 17 (cultural heritage) have direct connections to node 14 (recreation and tourism). The “knowledge system” (No. 16) and the value of “regional identity” (No. 18) have an indirect connection to node 14 through nodes 15 and 17 (Tables 4, 5, 6).

Table 5.

An example about the sensivility of a “12. Flood regulation” ecosystem service as a parent node to find at other nodes.

Node	Variance Reduction	Percent	Mutual Info	Percent	Variance of Beliefs
12. Flood regulation	661.3	100	2.26106	100	0.6163694
13. Water erosion regulation	42.56	6.44	0.18225	8.06	0.0198127
17. Knowledge systems	10.96	1.66	0.06268	2.77	0.0056131
10. Groundwater recharge	3.656	0.553	0.01660	0.734	0.0013876
9. Global climate regulation	2.298	0.348	0.00969	0.429	0.0005613
5. Timber	1.355	0.205	0.00770	0.341	0.0004867
16. Landscape aesthetics	0.9754	0.148	0.00377	0.167	0.0002722
8. Local climate regulation	0.3099	0.0469	0.00225	0.0993	0.0002128
11. Air quality regulation	0.182	0.0275	0.00051	0.0224	0.0000322
3. Crops	0.08343	0.0126	0.00042	0.0186	0.0000306
19. Regional Identity	0.07338	0.0111	0.00025	0.0112	0.0000179

Value of ecosystem services in the Thu Bon Estuary area

The value ES is an important result to assess the change in ecosystem quality over the last 30 years. In the Delphi method, the assessment includes 16 landscape unit/LULC (node 02) divided into four main groups: residential, agricultural, mangrove and wetland. In the research area, the authors list six large landscape types (node 01), each of which includes one or more different landscape unit/LULC. LULC changes easily across landscape types, while landscape types are less susceptible to change. Therefore, the area of a landscape type is equal to the sum of the LULC. The distribution area ratio of LULC in the landscape, when included in the BBN model, is based on GIS. Specifically, when evaluating the alluvial landscape (node 1) over a one-year period, the landscape's proportion is 100% and

the area proportion of LULC (node 2) corresponds with the GIS data when incorporated into the model. Finally, the BBN model's parameters automatically calculate the value to provide each ecosystem service.

Table 6.

An example about the sensivility of a “18. Cultural heritage” ecosystem service as a parent node to find at other nodes.

Node	Variance Reduction	Percent	Mutual Info	Percent	Variance of Beliefs
18. Cultural heritage	669	100	2.24831	100	0.6114432
19. Regional Identity	68.32	10.2	0.29968	13.3	0.0502799
16. Landscape aesthetics	5.91	0.883	0.03262	1.45	0.0038374
3. Crops	1.207	0.181	0.00938	0.417	0.0008787
4. Livestock	0.7599	0.114	0.00270	0.12	0.0002823
15. Recreation and tourism	0.2643	0.0395	0.00220	0.0978	0.0002191
17. Knowledge systems	0.255	0.0381	0.00215	0.0957	0.0002104

The values of ES in the research area can be classified into three different stages: the first stage from 1991 to 2001 was less affected by humans, the value fluctuating slightly. The second stage, up until 2015, was clearly influenced by urbanisation. Therefore, the value of ecosystem services has fluctuated significantly. The third stage has the remaining time. Although this period is relatively short to separate into a new stage, it has relatively reflected the immediate stable progress in value, gradually adapting to the stable development of urbanisation.

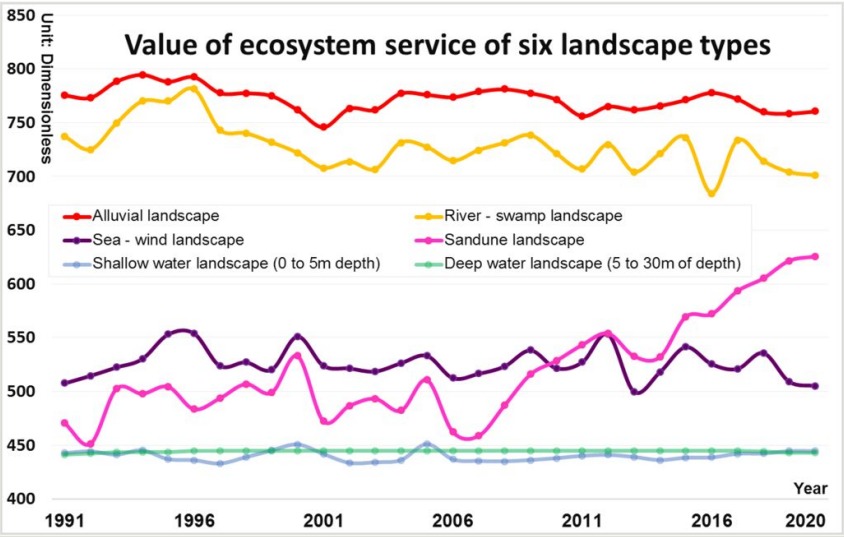

Figure 6.

Total value of ecosystem services of each landscape in Thu Bon Estuary, Quang Nam Province.

Overall, the values of the three ES groups have been relatively stable, only fluctuating in certain years. The total value that ecosystems provide to human life fluctuated from 627 points to 670 points. **The provisioning ES** is a group with a stable value of over 130 points per year and is the group with the smallest value of ES, in which, “fish and other seafood” and “crops” have the highest values (accounting for more than 52%). **The regulating ES** tends to decrease, from 234 points to 222 points, the rate of decrease compared to 1991 was 4.36% and fluctuated between the years. Specifically, in the three years from 1994 to 1996, the value of services increased (249 points), then the value began to decrease gradually and intermittently, the lowest value was 218 points in 2013 (down 31 points). In particular, ecosystem activities for “groundwater recharge” have the highest value (about 55 points) and “air quality regulation” have the lowest value (less than 30 points). The regulating ES have a similar relationship with each other; all six types of services have the same increase or decrease in value over the year. **The cultural ES** are the highest, but not stable group in 30 years, increasing in value from 280 points to 292 points, the growth rate being 4.4%. The highest value is “regional identity” (medium of 50-52 points) and the lowest value is “knowledge systems” (from 42 to 45 points) (Figs 6, 7).

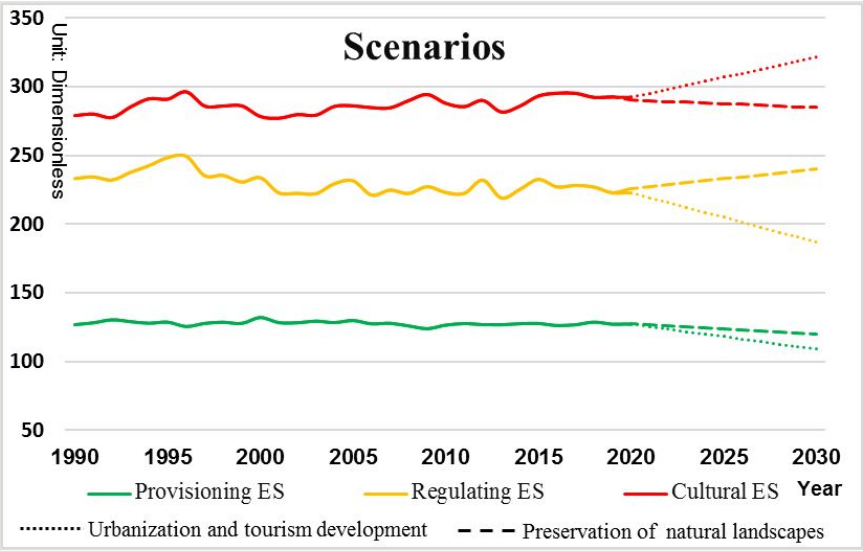

Figure 7.

Fluctuation of ecosystem services in “Urbanisation and tourism development” and “Preservation of natural landscapes”.

In Fig. 6, The total ES value of six landscape types from 1991 to 2020 tended to increase from 3,375 points to 3,480 points, but the growth rate of only 3% was not high. In particular, the “river - swamp landscape” with the largest acreage is the “alluvial landscape”; the smallest area is the “sand-dune landscape” and the “shallow water landscape (0-5 m depth)”. The “alluvial landscape” has the highest ES value, the average value over the last 30 years reached 772 points. The “river - swamp landscape” has the second highest value. These are two types of ecosystems that provide much higher values than the other four

landscape types. However, both of these types tend to decrease in value gradually and not continuously. The second group includes the “sand-dune landscape” and the “sea - wind landscape”. Both types of landscapes have continuously fluctuating values, especially the “sand-dune landscape” which has the strongest fluctuation. The remaining two landscape types have constant values and a low index range of 445 to 450 points. Although the area did not change much, the value of ES shows a relative difference. Due to the type of landscape, there has been a change in land use/cover and ecosystem function. For example, when people change from a mangrove coconut forest ecosystem to an aquaculture ecosystem, the value will be reduced. Mangrove coconut forests not only provide regulating values, but also include the value of providing seafood, especially cultural values. Meanwhile, the aquaculture ecosystem only provides natural or farmed seafood, the value of regulating and cultural ES being very low.

Scenario results

After two scenarios are selected, the data on land-use change continue to be included in the BBN model and the results of the changes in the ES values until 2030 are shown in Fig. 7. In the urbanisation and tourism development scenario, cultural ES values are experiencing a significant increase by 2030, accompanied by a noticeable decrease, at a faster rate, in regulating ES values. Ecosystems change ecological functions, increasing the risk of natural hazards. Rises in sea level during storms, combined with tides, cause the total water level in the coastal plains to reach 150 to 200 cm and increase the frequency of flooding in low-lying areas (urban areas, creeks and coastal areas and aquaculture areas). In the second scenario, which focuses on the preservation of natural landscapes, ES values will decrease slightly compared to 2020. The inherent values of an ecosystem remain stable without urban expansion. Preserving and enhancing heritage and relics is a must. There is a more noticeable increase in the values of the regulating ES group than those of the cultural ES group when nature is conserved. Naturally, this represents a gradual recovery of the environment, contrasting with the rapid destruction caused by urbanisation. Both scenarios have a tendency to reduce the value of provided ES. However, scenario 1 experiences a faster decline due to the dominant role of the tourism and service industries in the economic structure, while scenario 2 sees a milder decline as the affected areas still maintain the ability to provide services. In Figs 6, 7, the wrong number is based on the percentage (%) of each node's confidence level. The BBN model is not calculated, based on accuracy, but on model reliability, based on approaches to the probability of that outcome occurring.

Discussion

Potential use of BBN for ecosystem service assessment

The application of the integrated probability model in the BBN network for the assessment of multiple types of ES has proven successful in this study. Accordingly, the different strengths, weaknesses, opportunities and challenges of BBN in assessing ecosystem

services can be explained in Table 7. The model effectively addressed the data scarcity issue in the assessment of Thu Bon Estuary, especially regulating ES, by leveraging the expertise of 21 scientists, LULC maps and statistical data at the provincial, district and city levels, as done by Dang et al. (2021). It can be seen that the model has successfully evaluated multiple types of ES and the study provides detailed and specific results for 17 values according to the applicable directives compared to Duarte et al. (2016), Guerry et al. (2012). The model has high transparency, capable of bridging the gap between qualitative and quantitative methods of assessing ES values in the study by combining the calculated data on monetary values (providing ES and cultural ES) with the potential for objective provision (regulating ES).

Table 7.

Synthetic of strengths, weaknesses, opportunities and challenges of BBN in the model of ES.

Strengths	Weaknesses	Opportunities	Challenges
- There is a combination of professional knowledge and empirical data; - Easy to access model and usability for adaptive management; - Transparent data processing of uncertainties cases; - Multiple authentication tools other than data-driven authentication; - Data are updated as new knowledge and awareness become available.	- The ability to build complex model systems is limited due to the data being still subjective; - Current applications offer limited software integration capabilities.	- There are more and more studies using models for evaluation in ES and modelling ES; - Multidisciplinary waterfall approach: pairing different sub-models; - Expand current knowledge of BBN and related reasoning algorithms.	- Limited data availability; - Develop a single discipline model; - Limited public model acceptance.

This study addresses some of the limitations of previous BBN models. First of all, the study has given three indicators for the assessment of ES in terms of provision, regulation and culture. The expert-based matrix table has a wider scoring range, from 0 to 100. This offers experts more options to assign scores corresponding to ES on the one hand and the benefits from ecosystems can be understood in more detail on the other hand. The use of LULC as a representation for the provision of ES will better illustrate the direct human impact on the ability to create such services. Additionally, the model has provided a complex link between the functions and services of ecosystems. Integrating the correlation matrix and the SEM regression model has made it possible to simplify interactions and validate linkages between nodes in the developed BBN. Instead of ignoring the interactions between nodes or reducing the number of connections, the SEM regression model optimised between input variables, while minimising interaction in connections. SEM has reduced the limitation of modelling complex processes in the absence of feedback loops in BBN, as pointed out by Nyberg et al. 2006, McCann et al. 2006 and Castelletti and Soncini-Sessa 2007. Henceforth, the BBN model illustrates the relationship and structure of the network clearly, showing the interactions between ES to researchers without obscuring them, thus reducing the complexity of the provision processes of ES compared

to Barton et al. (2008). For example, node 18_“Cultural heritage” has a strong correlation with nodes 19 and 16. The remaining relationships are weaker. All of the services have such correlations, demonstrating different connections (as shown in Table 4). Three appendices of Table 4 make the results easily analysable, assessable and reviewable for accuracy/applicability to reality. In addition, the model also uses conditional probabilities to express the relationship between nodes.

Moreover, the BBN model requires minimal updates or may only necessitate additional data to align with the current situation during the study period. Therefore, the model consistently reflects the current state of knowledge. The data on the model are already representative and easily transferable from one location to another when quick information references are needed for decision-making processes related to the management and utilisation of ecosystems, as demonstrated by Xu et al. (2022). The model is also easily accessible by many different user groups. In addition, the developed model provides direct results on ES values on the gain and loss when changing land-use scenarios to planners and managers for direct use, without the need for additional applications or through any other intermediary. Moreover, the combined model includes analogue data and digital data to serve research purposes.

Impact of urbanisation and tourism development on sustainable use in estuarian regions

The result of the change in ecosystem service values was calculated using the BBN model in the Thu Bon Estuary, consistent with the sectoral development structure of the region and the whole province. It explains two trade-offs between estuarial ecosystem services through the change in LULC types.

The first is the process of tourism and urbanisation development. According to Table 1, the value of the cultural ES group is rated highest amongst the 3 ES groups (average 50–70). Most LULC types have experts showing high appreciation for cultural ES (KDL, RPT, SON, A1 etc.). The value of cultural ES increases as tourism develops. This is evidenced in Hoi An, right after the old town became a World Cultural Heritage Site in 1999. The significant development of large resorts along the coast has greatly enhanced the cultural environment. The number of visitors to Hoi An has increased rapidly; in 1999, there were only nearly 100,000 visitors and 17 hotel and motel facilities. By 2019, Hoi An had more than 7.6 million visitors and 624 accommodation facilities with more than 10,000 rooms, tourist villas and homestays. However, the Hoi An urban heritage is still preserved quite intact in terms of landscapes and architecture, as mentioned by Nguyen et al. (2024).

The second is natural hazards. The results of Table 1 of the Delphi method indicate a high assessment of the regulating ES for forests and wetlands (70-90). This demonstrates their significance in mitigating natural hazards. However, in Thu Bon Estuary, the area of forests and wetlands is small and easily subject to changes, leading to rapid degradation that affects life, such as extensive and prolonged floods (which can reach a depth of one metre (Hieu 2007). Storm Nari (2013) destroyed more than 80,000 hectares of fruit and forestry

trees. The expansion of urban and tourism types (ODT, KDL, CDG, A2 etc.) has a low assessment value (5–20) in the regulating ES group. In the Thu Bon Estuary, erosion has continuously penetrated inland at a rate of 2-3 m to 20-30 m/year; even in the rainy season, floods can be as high as 40-50m/year, but there is a process of rapid backfilling and accumulation of a large amount of sludge in the dry season according to Thien and No (2012). In 2020, the Cua Dai area is strongly eroded to significantly strong from 3-10 m/year, even over 10 m/year according to Liem et al. (2020). The rest is due to the urbanisation process in Hoi An City and the expansion of residential areas in Duy Xuyen District.

The two scenarios give a more objective view of the trade-offs of ES values for different types of land use/cover. In scenario 1, the trade-offs and losses are more apparent when moving towards tourism development and urbanisation. When prioritising urbanisation and tourism development, the ability to ensure the supply and demand for cultural ES is stable because these are products that humans can easily create and utilise and "long-established" resources offer many advantages. However, when the emissions of an urban area increase, environmental pollution, population carrying capacity in a territory and other problems increase; the demand is insufficient for environmental treatment and protection due to the concretisation of forest systems and green cover. The clear evidence is the substantial reduction in the regulating ecosystem services. As a result, excess supply leads to socio-economic conditions that exceed the limits of the sustainable development circle. Therefore, the key issue is protecting the natural environment.

Conclusions

A system of different evaluation indicators for assessing estuarial ES was provided in this study. Based on this system, a Bayesian Belief Network for assessing the interplay between estuarial ES and natural and social factors was successfully developed and tested for a particular region in Vietnam. Accordingly, the BBN model can effectively resolve cases deemed uncertain by integrating expert knowledge in the case of data scarcity. In estuaries in Vietnam, tourism development, urbanisation and natural disasters have altered the values of ES over the past three decades. In general, the values of cultural ES increased, whereas the values of regulating ES decreased over time. The transformation in land uses/covers, although it has accelerated urbanisation, leads to an ecological imbalance. Based on the evaluation of estuarial ES, managers are able to select suitable land-use policies in order to attain a state of equilibrium in the provision of long-term ecosystem services. Furthermore, it is imperative that policy-makers prioritise the growth of protective forest ecosystems along the Thu Bon Estuary's coastlines so as to prevent inundation, enhance air quality and regulate erosion. Additionally, the developed BBN is not only used for some estuarial regions in Vietnam, but also for other regions in the world in the future.

Appendix

Appendix 1

Indicator table for assessing estuarine ecosystem services in Vietnam (Table 8).

Table 8.

Indicator table for assessing estuarine ecosystem services in Vietnam.

Ecosystem services		**Indicators**
Provisioning services	*Crops (human nutrition)*	Quantity of plants usable for human nutrition.
	Livestock	Capability/ quantity of domestic animals useable for nutrition and related products (dairy, wool).
	Timber	The mass of wood useable for human purposes (e.g. construction,...)
	Fish and Seafood	Quantity of seafood, algae useable for food, fish meal and fish oil.
	Minerals	Minerals extractable close from surface or above surface (e.g. sand for construction, lignite, gold, salts).
Regulating services	*Water flow regulation*	Water cycle feature maintenance (e.g. water storage and buffer, natural drainage, irrigation and drought prevention).
	Local climate regulation	Changes in local climate components like wind, precipitation, temperature, radiation due to ecosystem properties.
	Global climate regulation	Long-term storage of potential greenhouse gases in ecosystems.
	Air quality regulation	Capturing/filtering of dust, chemicals and gases from air.
	Flood regulation	Soil retention and the ability to prevent and mitigate soil erosion and landslides.
	Erosion regulation	Protect and minimise disasters related to floods, storms, erosion,...
Cultural services	*Recreation and tourism*	Outdoor activities and tourism relating to the local environment or landscape, including forms of sports, leisure and outdoor pursuit.
	Landscape aesthetics	Visual quality of the landscape/ecosystems or parts of them influencing human well-being and the need to create something, as well as the sense of beauty people obtain from looking at landscapes/ecosystems.
	Knowledge systems	Environmental education, based on ecosystems/landscapes and knowledge in terms of traditional knowledge and specialist expertise arising from living in this particular environment.
	Cultural heritage	Values that humans place on the maintenance of historically important (cultural) landscapes and forms of land use (cultural heritage).
	Regional identity	Ecosystem elements or processes contribute to a person's personal identity (sense of belonging) or strengthen people's group identity.
	Natural heritage	The existence value of nature and species themselves, beyond economic or direct human benefits.

Appendix 2

The SEM model to set up a BBN for assessing esturian ecosystem service (Fig. 8).

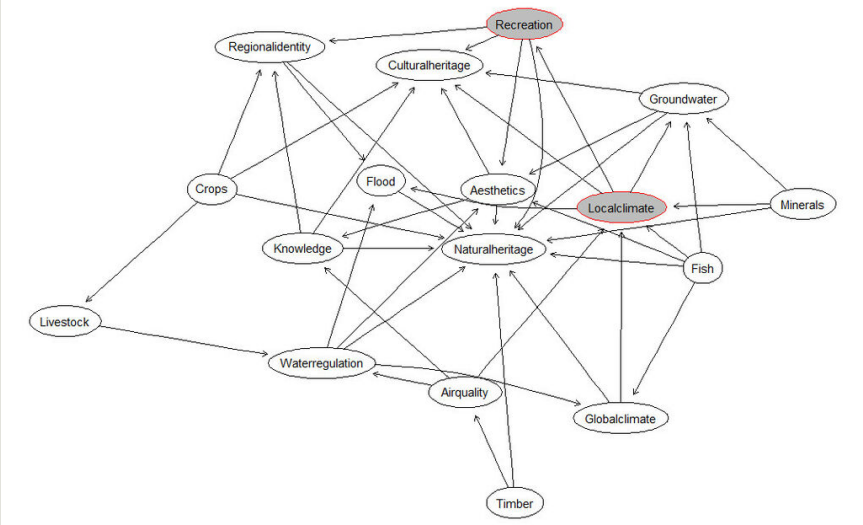

Figure 8.

The SEM model to set up a BBN for assessing esturian ecosystem service.

Appendix 3

A linear chart showing the correlation between ecosystem services (Fig. 9).

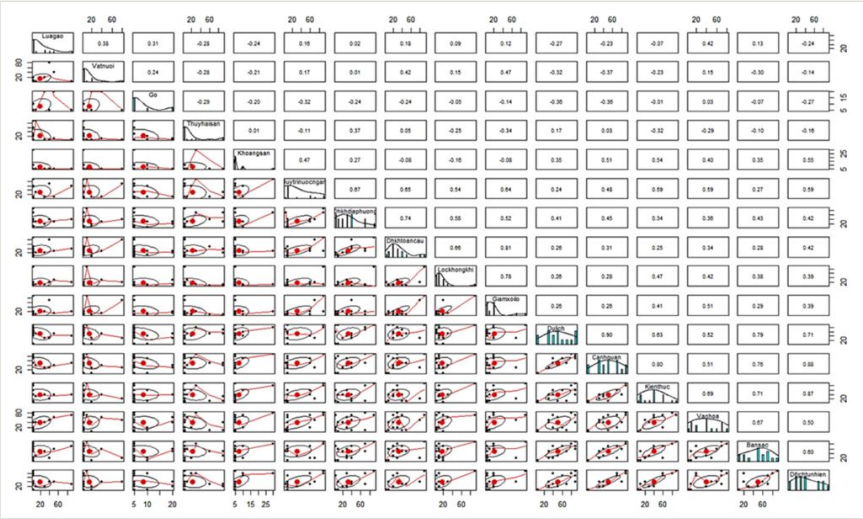

Figure 9.

A linear chart showing the correlation between ecosystem services.

Appendix 4

Field pictures of four major ecosystem groups (Fig. 10).

Figure 10.

Field pictures of four major ecosystem groups.

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Conflicts of interest

The authors have declared that no competing interests exist.

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Endnotes

*1 www.eorc.jaxa.jp/ALOS/en/dataset/