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Supporting spatial planning with a novel method based on participatory Bayesian networks: An application in Curaçao

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ABSTRACT

Land use change is a major driver of environmental degradation, necessitating appropriate planning to navigate trade-offs between societal objectives and ecological impacts. Sound planning is limited in some regions by data scarcity and incomplete scientific knowledge on local dynamics shaping development of land. In this paper, we present a novel expert-based participatory approach that uses Bayesian networks to determine land use suitability and potential conflicts for emerging land uses. This method encompasses a workshop phase for building suitability models for different sectors, data assembly and preparation, spatialization of networks, and iterative validation with experts. Mapped suitabilities for all land uses were used to assess potential competition for land across sectors and to quantify alignment of the expert-modeled outcomes with established land use policy. Applied to Curaçao, a data-poor environment in the Caribbean facing high land use competition, the method enabled the construction and parameterization of 5 Bayesian networks driven by 35 spatial input datasets generated through various methods from participatory mapping to social media analysis. Overlap in suitable locations for conservation and tourism development along segments of the coastline and roadsides of the western island highlight potential conflict stemming from coincidence of desirable natural amenities and ecologically sensitive areas. Results yield key insights that can drive discussion and inform policymakers and spatial planners as they navigate tradeoffs and seek optimal use of limited land resources. Process-based suitability predictions and knowledge of underlying drivers can also enable exploratory analysis into possible future scenarios of change.

1. Introduction

Rapid and extensive land use change has dramatic impacts on the environment and society (Winkler et al., 2021) and is one of the key processes of global environmental change (Searchinger et al., 2018; Steffen et al., 2015). Land use planning attempts to influence these dynamics so that land use configurations are achieved that meet the diverse needs of society and protect the environment (Verburg et al., 2015). Especially in contexts of limited or diminishing land resources, planners depend on evidence to support this balancing act and inform these complex impactful decisions (Mycoo et al., 2017). Decision support tools are essential in supporting effective land use planning as they provide planners with the necessary information and tools to make informed decisions, balance competing demands, and meet societal and environmental objectives in the near and long term (Janssen et al., 2008; Lestrelin et al., 2017; Matthews et al., 1999).

One tool for informing land use planning to better ensure efficient and sustainable use of land resources is through *land suitability analysis* (LSA). LSA aims at identifying the most appropriate spatial pattern for future land uses according to specified requirements, preferences, or predictors of activity (Malczewski, 2004). LSA is therefore a means to optimize land use through an alignment of land properties and user needs. Land suitability approaches usually target a specific type of land use, as in crop suitability or agricultural land suitability analysis (Akpoti et al., 2019). Simultaneous land suitability analysis, through representation of multiple land uses in tandem, is a logical extension that seeks to illuminate the dynamics between sectors, thereby enabling more nuanced discussion over allocation (Morales and de Vries, 2021; Rodriguez-Gallego et al., 2012). Such approaches can be instrumental in identifying potential conflicts and helping to limit tradeoffs, avoid land use risks, predict future land use alternatives, and maximize the economic, social and environmental benefits of limited land resources

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(Dong et al., 2021; Jing et al., 2021). Nevertheless, simultaneous land suitability analyses are less common in existing literature, due in part to the difficulty of representing fields with disparate priorities and distinct conceptualizations of land suitability, the complexity and uncertainty inherent to these systems, and imbalance in knowledge or data on these systems (Brown and Raymond, 2014; Morales and de Vries, 2021).

Besides the apparent shortage of multi-sector approaches in land suitability analysis, the most popular approaches, like Multi-Criteria Evaluation (MCE) or the Analytical Hierarchy Process (AHP), are largely deterministic and do not account for uncertainty linked to variable interactions and data quality realities (Bagheri et al., 2013; Chandio et al., 2013; Gebre et al., 2021; Mas et al., 2012; Morales and de Vries, 2021). Inaccuracy or exaggerated confidence in depictions of suitability can spur ill-advised management decisions which inadvertently incite conflict or squander limited land resources amid narrow windows of opportunity (Uusitalo et al., 2015). In many contexts, such as small island developing states, spatial data simply do not exist to support a robust deterministic framework. Supplying evidence for spatial planning in such contexts, particularly through suitability analyses, remains unaddressed as a research challenge (Gessesse et al., 2023). Increasingly, local stakeholder and/or expert knowledge is leveraged in order to offset data deficiencies and expand upon normative system representations (Hewitt et al., 2014; Mallampalli et al., 2016; Voinov et al., 2016).

Participatory systems modeling offers a means to capture and represent the complexity inherent to land suitability by engaging with implicit and explicit knowledge and subjective reasoning of stakeholders to create formalized and shared representations of reality (Voinov et al., 2018). One approach to deal with uncertainty and express the joint behavior of a large number of interrelated variables is the use of Bayesian networks (BNs) (Barons et al., 2022; Barbrook-Johnson and Penn, 2022). Bayesian networks are directed (acyclic) graphs of variables linked through conditional probabilities (Marcot and Penman, 2019). The graphical structure of a BN denotes causalities in the modeled system, granting improved transparency over black-box (empirical) models and facilitating communication with stakeholders (Stritih et al., 2020; Voinov et al., 2018). Other advantages of BNs lie in their ability to integrate both qualitative and quantitative information and their explicit treatment of uncertainty – both vital when attempting to represent complex and variable systems with limited data. BNs are particularly useful for cases which integrate several system components and where relationships between variables are non-linear and complex (Chen and Pollino, 2012). While BN use has proliferated across many disciplines, they have seen only limited use in spatially explicit studies of land use suitability or change (Marcot and Penman, 2019). Among these, a handful have engaged stakeholders and experts directly in order to elicit model structure and parameters (Andriatsitohaina et al., 2020; Celio et al., 2014; Celio and Grêt-Regamey, 2016; McCloskey et al., 2011; Meyer et al., 2014; Nascimento et al., 2020; Stritih et al., 2020).

In this contribution we present a novel expert-based approach using Bayesian network models for the spatially explicit prediction of land suitability, overcoming data scarcity through iterative integration of expert knowledge for different sectors. The method was tested on the island of Curaçao (a Lesser Antilles island country) through a parallel elicitation process with local expert groups from conservation, urban fabric, tourism, and agriculture sectors. Modeled outcomes were used to identify the extent and relative intensity of potential conflict between sectors and to examine agreement between predicted suitability and land use desirability, as reflected by prevailing spatial policy. Through this case, we seek to illustrate the potential for such a participatory modeling framework to support spatial policy planning.

2. Materials and methods

2.1. Summary of the overall approach

The approach starts with (1) a scoping phase to determine predominant land use sectors; identify the experts affiliated with these sectors; and to determine data availability. This is followed by (2) facilitation of workshops wherein sectoral experts construct consensual Bayesian networks to predict land use suitability for their respective sectors. In step 3, data, or acceptable proxies, are assembled and (pre)processed to correspond with all specified inputs. The models are then spatialized to depict suitability across the entire study area. In step 4, model outputs are reviewed by expert groups and the models – and input data – are modified where necessary so that outcomes and the process representation matched their expectations. In our application the final modeled results were applied, in step 5, to identify the extent and relative intensity of potential competition across sectors and to examine agreement between predicted suitability and current spatial policy (Fig. 1).

2.2. Study area

Curaçao (12.2 deg N, 69.0 deg W; land area of 444 km2) is an island in the Leeward Antilles of the southern Caribbean Sea, north of the Venezuelan coast (Fig. 2). Home to roughly 150,000 people, the island surface is characterized by sprawling (sub)urban development concentrated around Willemstad's downtown core in the south-east, and towns, brushland, and dry tropical forest in the less densely developed west. Tourism activity – which is predominately clustered along the Southwestern coast near to the inner city - drives much of the island's economy, amounting to 18% of the total in 2015 when 23% of jobs on the island were sustained directly or indirectly by the sector (Curaçao Tourism Board, 2015). The island is ringed by a continuous fringing reef, most prevalent along the South-western leeward coast, whose ecosystem services have been valued at around $445 million dollars per year for the tourism and fishing sectors alone, amounting to nearly 15% of the island's GDP (Sustainable Fisheries Group, 2016). Curaçao faces increasing pressure to develop its coastal regions, which can result in irreversible damage to valuable habitats (Waitt Institute, 2018; Mycoo, 2021). While conservation areas have been established in the interest of preserving natural and cultural resources, Curaçao's land area is inherently constrained and development pressures imposed by tourism, residential, and commercial sectors continue to mount (Dinica, 2012; UNOPS 2018). In addition, while the majority of the nation's food is imported, there are growing calls for improved self-sufficiency through local production and an expansion of the agricultural sector (United Nations Development Programme, 2018). There is a strong need for spatially explicit insights into land use patterns and underlying pressures in order for the nation to limit tradeoffs in meeting and sustaining societal objectives.

2.3. Scoping

The scoping phase of this study entailed a literature review (including grey literature) and survey of available spatial data alongside informal interviews and in-person meetings with local experts with a stake in land management, ranging from private landowners to government ministries. Interviews followed a snowball sampling strategy. The primary objective of this effort was to compile the information necessary to arrange and facilitate systems modelling workshops with experts. Through these preliminary assessments, we sought to identify the key sectors and associated land uses as well as the major influencing factors shaping land use change. Additionally, the scoping effort served to identify key experts affiliated with these sectors whose knowledge or familiarity collectively spanned the area of study. While representatives

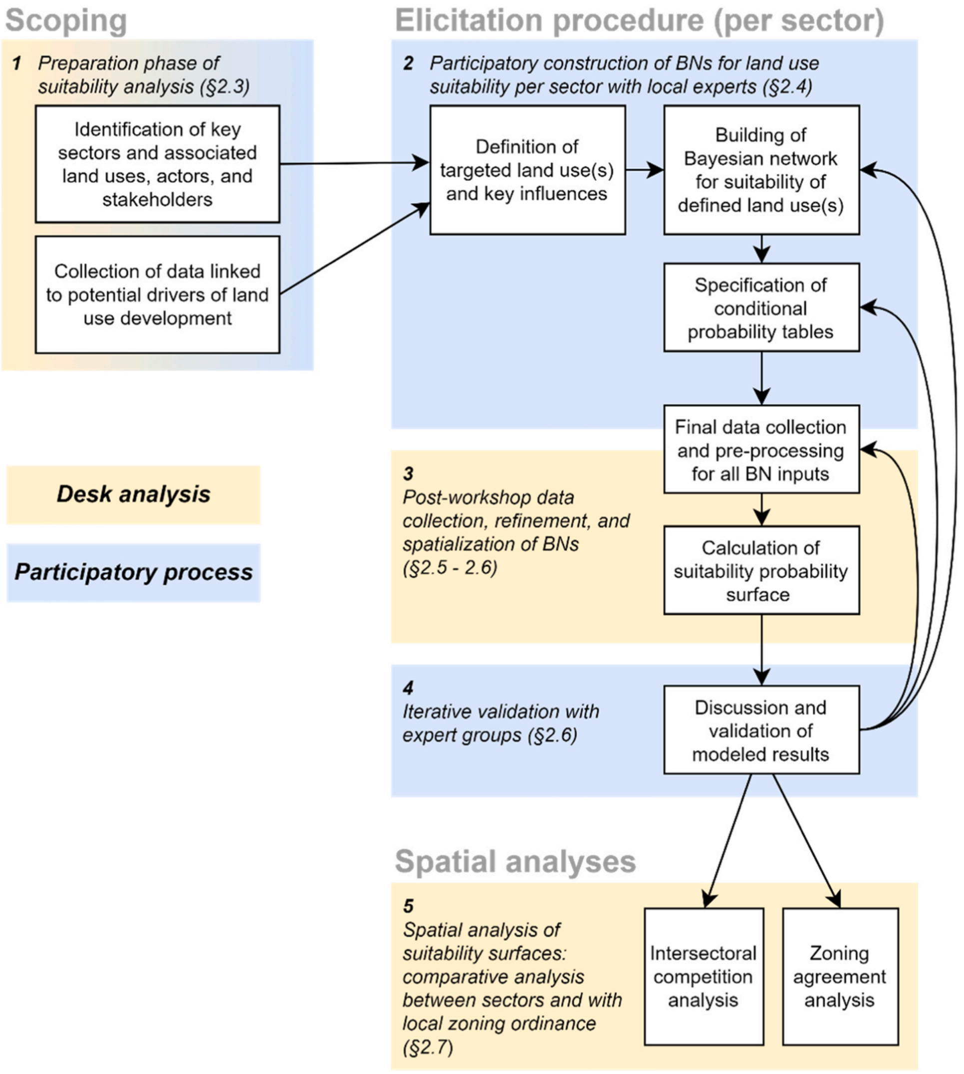

Fig. 1. Methodological approach flow diagram.

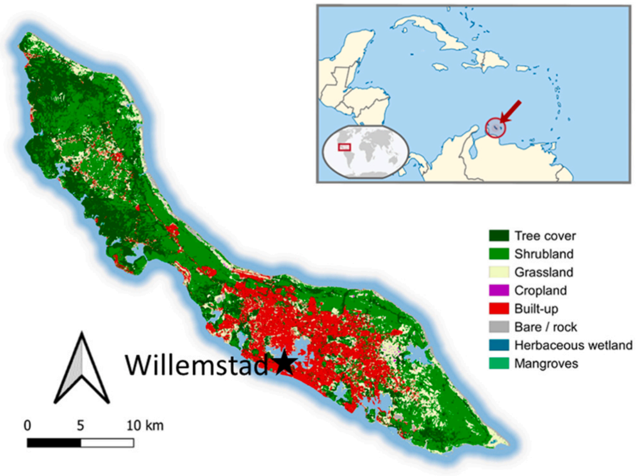

Fig. 2. Curaçao land cover (excl. Klein Curaçao) from WorldCover 2021 (Zanaga et al., 2022).

for each land use were sought who had a generalized knowledge of or experience in their sector, potential participants were not limited to those originating from 'recognized' civil society. Instead, expert identification via snowball interviews allowed for a localized definition of expertise, inviting engagement with actors with unique stakes in land management. Lastly, this process involved assembly and review of existing datasets (and notable data gaps) to inform forthcoming co-modelling exercises and better ground the process in local data realities.

2.4. *Model elicitation with local experts*

Workshops were conducted separately with expert groups from the 4 predominant land use sectors: conservation, tourism, urban-fabric, and agriculture. A total of 12 experts took part in the participatory process which aimed to produce fully parameterized consensual Bayesian network models of land suitability for the primary land use(s) associated with their sector. Facilitation was carried out so as to encourage equal and open participation while yielding models which balanced parsimony with detail (Marcot, 2017; Marcot et al., 2006). Working in small groups of 2–4 participants allowed for in-depth debate and consensus-building. Working with larger, more diverse groups is feasible - and could be necessary when working at broader spatial extents - but will necessitate a greater emphasis on consensus-building. In addition, when working at larger scales and with more experts, modular sub-networks (or network fragments) could be elicited that represent different components of a sector's land suitability system and then subsequently merged to form a single network (Chen and Pollino, 2012).

The workshop procedure followed five main steps: First, research objectives and principles of the modelling exercise were presented and participants were familiarized with themes of land use change and land suitability. Together, we then identified which land use(s) to represent, with the possibility of distinguishing sub-classes. Afterwards, relevant biophysical and socio-economic factors that render land more or less suitable for their selected use(s) were discussed. Selected factors were independent, spatially variable, and applicable over the entire study area. We then discretized continuous variables into appropriate intervals or so-called node states. Next, we elaborated model structures using intermediate, or latent nodes, to cluster inputs that have a combined or related effect on land use suitability (Marcot et al., 2006). In this process we sought balance between detail and parsimony by (1) limiting the depth of the models to four or fewer layers, (2) restricting the number of parent nodes (3) using the fewest discrete states necessary within each node. Finally, we parameterized models through assignment of conditional probabilities linking child and parent nodes (workshop details are elaborated in Appendix A).

2.5. *Data collection and processing*

Following the elicitation of all sectoral models, datasets were attained and processed for all input variables according to the definitions set by experts. For some inputs, simple raster calculations or OpenStreetMap queries were performed using publicly available data. For others, coordination with experts and more advanced data processing methodologies were necessary to build datasets or derive reasonable proxies. Such methodologies included social media analysis, participatory mapping, and spatial analysis like viewshed analysis. Input node definitions, data sources, and methodological aspects for all sectors can be found in Appendix B.

2.6. *Spatializing and validating models*

We used Netica software (Norsys, 2011) to digitize the expert models. Sensitivity of each target node (land use suitability) to input nodes was calculated in terms of entropy reduction, or Shannon measure of mutual information (See Appendix E) (Andriatsitohaina et al., 2020; Norsys, 2011; Pollino and Henderson, 2010). The gBay tool (Stritih et al., 2020) was used to link network nodes to raster datasets. Inference was performed for each pixel of the input data and output as a probability distribution across the possible states of child nodes for each spatial unit (Stritih et al., 2020). Individual raster files were generated for all intermediate nodes and for the ultimate land suitability node of each model.

In this study, final model structures and parameterization are the result of a validation process carried out iteratively within respective groups of experts. A structured review of each model was carried out to evaluate the Bayesian networks in terms of structure, node discretization, and parameterization to determine whether they were reflective of expert expectations, as suggested in different studies (Andriatsitohaina et al., 2020; Catenacci and Giupponi, 2013; Celio et al., 2012). Each model version was run and maps produced for intermediate and final suitability variables so that expert groups could evaluate predictions of the iteration at hand. Alongside overall model performance, this iterative validation process allowed experts to review datasets assigned to input variables. Outputs for the updated model versions were circulated for a final round of feedback as in similar studies (Catenacci and Giupponi, 2013). While acknowledging certain limitations, particularly surrounding data availability, final models received positive feedback and were regarded as reasonable representations of their respective complex problems.

2.7. *Mapping potential land use competition and spatial policy agreement*

Across sectors, distinct interpretations of suitability and probability values can result in highly varied ranges and distributions of scores. Therefore, upper percentiles of each suitability map are compared to examine the overlap of priority areas for each sector. For each model output, 75th, 90th, and 95th percentile values were calculated and their spatial coincidence assessed against all other models across the study area. Comparisons at higher percentiles connote a greater degree of intensity of suitability overlap.

This analysis further explores the relative alignment of expert-predicted suitability and planned land use delineations as laid out in the Island Development Plan 1995 (Eilandelijk Ontwikkelingsplan Curaçao, 1997). The EOP establishes area designations for a number of zone types, including urban residential areas, inner city, industrial areas, airport, touristic areas, agricultural areas, conservation areas, (urban) park areas, rural areas, and open land (Appendix A3). The document describes permissible uses for each zone alongside general planning objectives such as a 'concentration policy' - to limit urban sprawl and concentrate economic activity - and facilitation of growth in the tourism sector. The longstanding EOP, due in part to its age, has been the subject of criticism by developers and environmental advocates alike and numerous governments have called for its revision or modernization (Waitt Institute, 2018; Porter et al., 2016).

Two approaches were applied to explore agreement between the suitability maps and the EOP: zonal statistics to assess the sectoral suitability model outcomes for each zone type, and spatial correlation analysis of suitability maps with the best-matching (most appropriate) zone type(s). Suitabilities are compared to zoned areas that have yet to be converted to their intended use*;* here referred to as 'potential zoned area'. In the absence of an official and precise map of the functions for which different land covers are currently used for the island it was assumed that all relevant land cover within a zone represents land use in full compliance with zoning regulations. Thus, for example, all built-up areas within 'Tourism' zones were assumed to be attributed to tourism land use(s) and, for conventional agriculture, all areas within agricultural zones with 'cropland' cover was assumed to correspond with the modelled use. An amended WorldCover 2020 (Zanaga et al., 2021) land cover product (used as the basis of some model inputs) was used for this analysis. For conservation, in lieu of a land cover proxy, 'potential zoned area' was delineated as all conservation- or park-zoned area, minus those areas that are already managed under contract as national parks. To limit the effects of spatial auto-correlation, a random balanced subsampling scheme with a global minimum distance of 60 m was applied: 2500 points were selected from within the 'potential zoned area' and 2500 from beyond the zone in question for each suitability-zone pair (Serneels and Lambin, 2001; Stolle et al., 2003). A point-biserial (Pearson's) correlation test was performed between mapped suitability probabilities at these points and the dichotomous variable of presence (or not) of 'potential zoned area'.

3. Results

3.1. *Expert stakeholder models*

Iterative sessions with sectoral experts yielded 4 Bayesian network model structures (Fig. 3) and underlying conditional probability tables for intermediate and target variables (Table 1 & Appendix D). The conservation model predicts land suitability for conversion to 'nature park' area or equivalent protection measures. The urban fabric model predicts suitability for a macro-class of land uses including residential and supporting commercial uses/amenities which experts describe as occurring mostly in tandem on the island. The model built by experts from the tourism sector predicts land suitability for tourism lodging and facilities. The agricultural group distinguished two separate land uses – conventional and structural/soil-free agriculture – modeled independently using distinct conditional probability tables but with a common network structure. All models feature 3 or 4 'layers' and between 8 and 13 inputs, ranging from biophysical conditions (e.g., slope, soil type) to

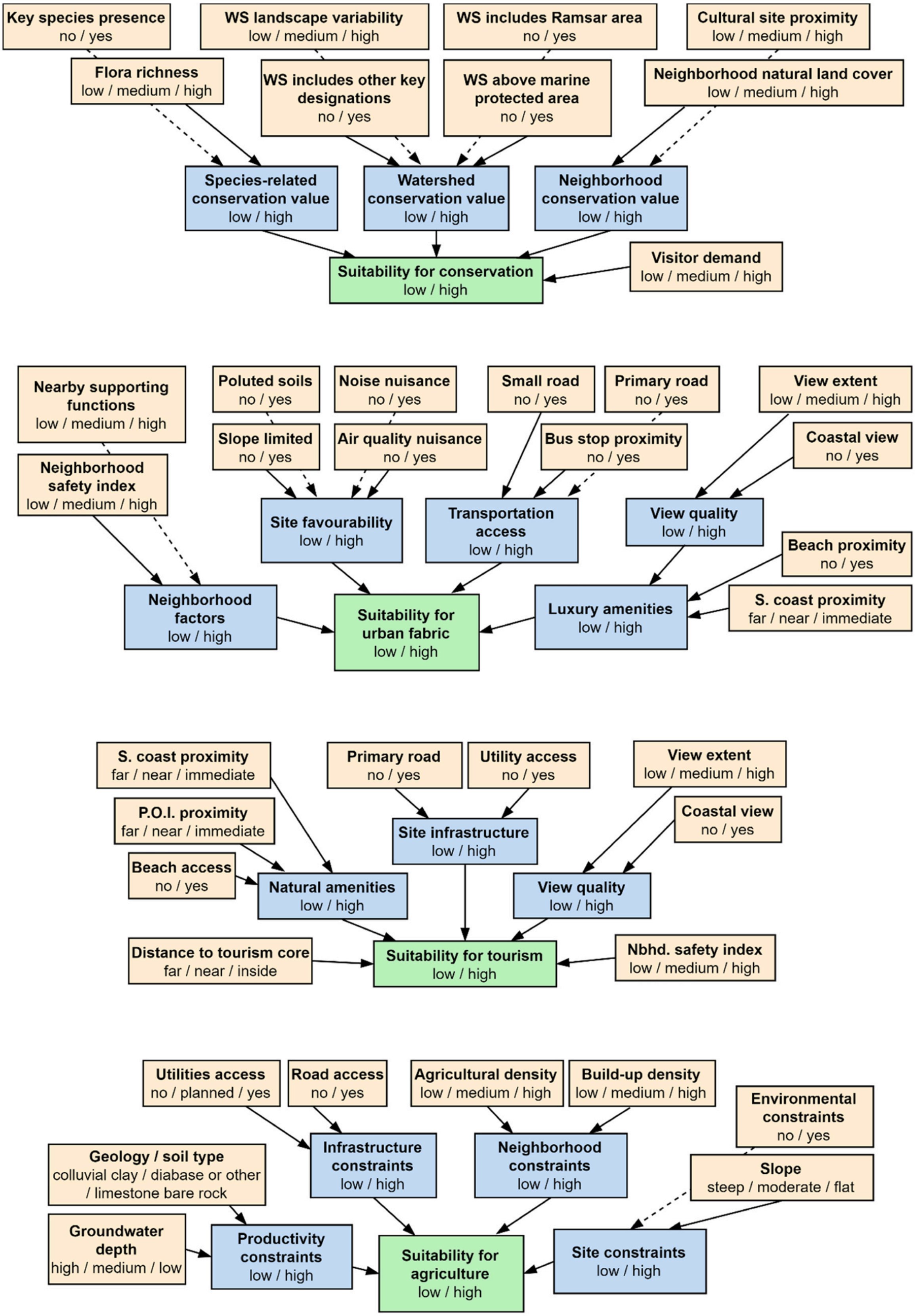

Fig. 3. **:** Bayesian networks for conservation, urban fabric, tourism, and agricultural land suitability. WS = watershed, Ramsar areas are wetlands of international importance, See Appendix B for additional details on all input variables and Sections 3.1.1–4 for explanations of intermediate nodes.

Table 1
Sample conditional probability table (CPT) for intermediate node 'Species-related conservation value' of the conservation model. See Appendix A4 for all tables.

Parent node states		Outcome states (Species-related conservation value)	
Flora richness	Key species presence	Low	High
low	no	65	35
low	yes	0	100
medium	no	25	75
medium	yes	0	100
high	no	10	90
high	yes	0	100

socioeconomic indices for visitor demand or neighbourhood safety. Continuous variables were discretized into 2 or 3 states, thresholds for which are elaborated in Appendix A4. The networks all exhibit some degree of dependence upon existing land use/cover conditions reflected, for example, through neighbourhood effects and/or infrastructure networks. Some variables are common to multiple sectoral models - suggesting overlapping suitability drivers - but are framed and parameterized distinctly, per consensus of the respective expert groups.

3.1.1. Conservation

The experts responsible for the conservation model identified 9 key spatial factors influencing suitability for conservation land uses (Fig. 3). Intermediate nodes for 'species-related', 'watershed', and 'neighbourhood conservation value' were introduced as latent variables to summarize the major themes denoted in the diagrams and capture the joint influence of several variables on the final outcome. Alongside biodiversity and habitat-related indicators the group sought to represent more diverse, human elements of conservation, including issues of access and preservation of cultural heritage through a proxy variable for visitor demand and presence of cultural heritage sites. Experts introduced 'watershed conservation value' to account for connectedness of areas via surface runoff, the value of riparian corridors, and other watershed dynamics that impact the state of biodiversity. This model also places emphasis on existing spatial policy or other representations of conservation priorities through its incorporation of Ramsar, Marine protected areas, and other key designations – thereby, in effect, endorsing these past decisions and indirectly incorporating past evaluations of suitability into the model.

3.1.2. Urban fabric

Urban experts, in their model of land suitability for urban fabric, identified 13 spatial variables as key influencing factors, with intermediate variables of 'site favourability', 'view quality', 'luxury amenities', 'neighbourhood factors' and 'transportation access'. The group sought to represent diverse development interests in their model by accounting for factors driving both high-end development and sprawling urban expansion. Probabilities for 'Site favourability' are shaped by the combined influence of a group of inputs that collectively denote (site-specific characteristics that act as) deterrents to development – soil pollution, impacted air quality, noise nuisance, and prohibitive slopes. The intermediate variable 'transportation access' is informed by the positive influence of small or large road access and proximity to existing public transportation stops. 'Neighbourhood factors', in their model, summarize the combined effect of more regional conditions: neighbourhood safety perceptions and density of so-called "supporting functions" (education facilities, churches, parks, etc.). 'View quality', as an intermediate node, allowed experts to define overall view quality as a factor of relative topographical advantage and line of sight to coastal waters.

3.1.3. Tourism

Tourism experts identified 9 input variables, several of which were grouped for their combined impact upon suitability as 'natural amenities', 'site infrastructure', or 'view quality'. The 'natural amenities' score is based on the availability of or access to desirable areas or environmental features, including broader attractions such as the southern coast and more specific features such as sandy beaches and cultural heritage and dive sites. Experts sought to emphasize the strong dependence of emerging developments on existing infrastructure networks, summarized in their model with the intermediate variable 'site infrastructure'. 'View quality', as above, is based on indices representing coastal view opportunity and overall viewshed extent. One core principle of their model is that different areas of the island will follow distinct suitability rules depending on a site's 'distance to the tourism core'. This is reflected in the parameterization of the conditional probability tables (Appendix A4), which shows the relative and combined influence of the remaining nodes shifting depending on the state of the 'distance to tourism core' node.

3.1.4. Agriculture

The agricultural model features 8 inputs: driving factors that influence land suitability through their combined behaviour as 'infrastructure constraints', 'productivity constraints', 'site constraints', or 'neighbourhood constraints'. 'Infrastructure constraints' summarize the effects of access and connectivity on the potential emergence of agricultural land uses. 'Productivity constraints' describe the combined influence of key (hydro)geological conditions whereas 'site constraints' summarizes potentially prohibitive site features such as excessive slope or polluted or hypersaline soils. Lastly, 'neighbourhood constraints' refer to the combined effects of nearby land uses on an area's suitability. Through these neighbourhood variables, the experts sought to represent complex dynamics of competition, security, and mutualism between the modelled land use and pre-existing uses. The agricultural group used the same network structure to model both conventional and structural (or "soil-free") agriculture land uses, but with different conditional probabilities. Conventional agriculture exhibits greater dependence on environmental and productivity constraints whereas suitability for structural agriculture is more strongly shaped by infrastructure and slope conditions (see Appendix A4).

3.2. Modeled suitability

High suitability probabilities (>60%) are predicted for large swaths of the island (70–85% of the total surface) for conservation, urban fabric, and the two agricultural uses (Fig. 4 & 5). The tourism model, on the contrary, identifies only 8% of the island as having a 'high' probability of suitability. The conservation map, with a median value of 93% across all pixels, suggests that most of the island is suitable for conservation measures. Urban fabric suitability is also predominately high, with a median value of 76% - highest values appear in areas of existing development or with road access and lowest values are found in inaccessible areas with high slopes. Highest scores for tourism cover are concentrated in a smaller area, mostly along the southern coastline and near the urban center. The agriculture suitability maps both show wide coverage of highly suitable land, particularly in patches across the central-Eastern island as well a handful of scattered patches in the west - lower values appear along the coastline and the middle section of the island. Higher minimum suitability probabilities for conservation, conventional agriculture, and structural agriculture models (see Fig. 5 and Appendix G) illustrate a reluctance among experts to deem land absolutely unsuitable for their sector. Meanwhile, maximum values yielded for tourism, conventional agriculture, and structural agriculture reach only 86, 84, and 89% respectively.

3.3. Potential land use competition

The spatial overlap of the most suitable areas from each sector indicate sites of potential competition between uses (Fig. 6). Highest-probability areas for conservation suitability overlap with areas

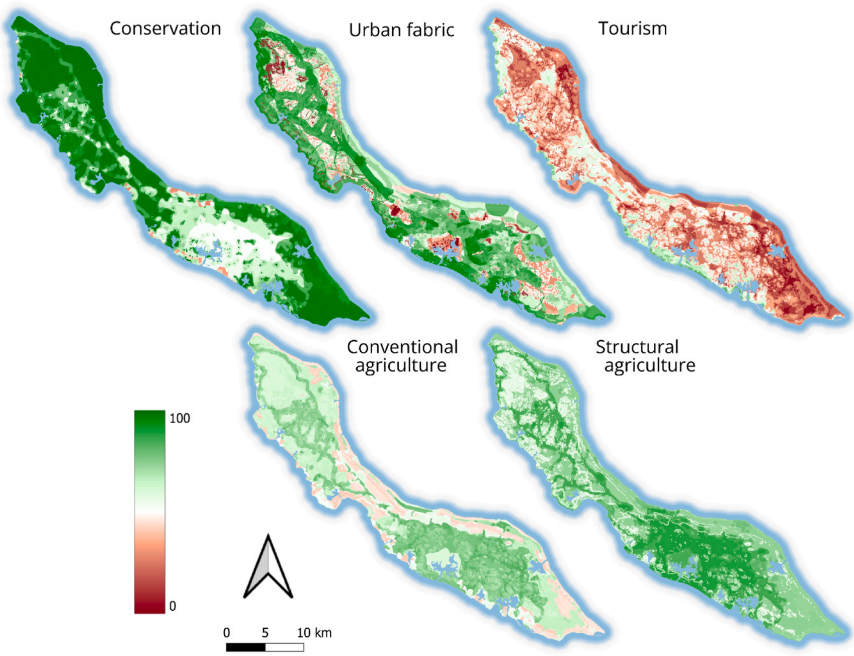

Fig. 4. Probability maps for high suitability per sector (see Appendix F for relative depiction of suitability).

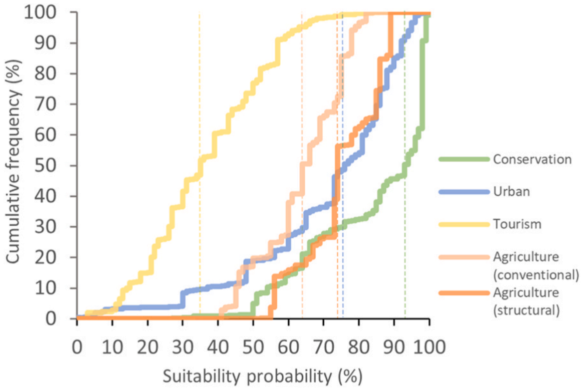

Fig. 5. Cumulative frequency of suitability scores in sectoral model outputs. Vertical dashed lines represent median values per sector.

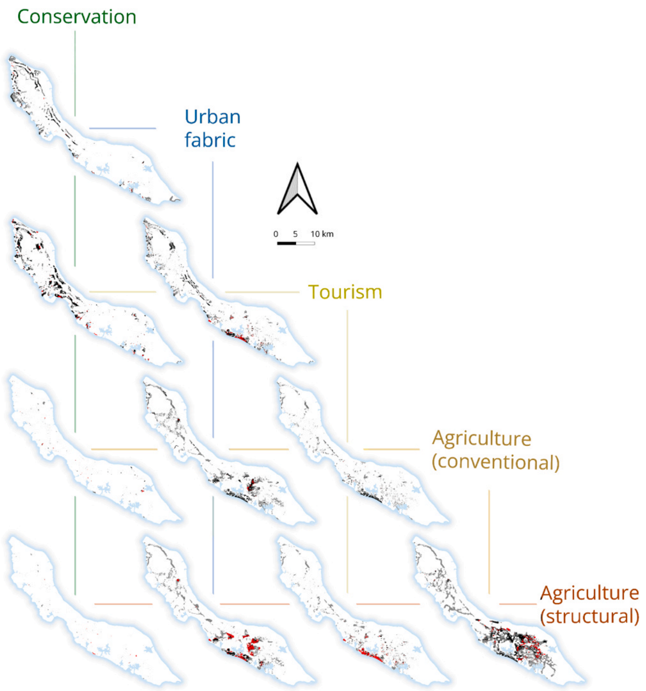

Fig. 6. Suitability overlap between sectors at 75th (grey), 90th (black), and 95th percentiles (red) (See Appendix 6 for conflict per sector).

deemed similarly favourable for tourism and urban use in large swaths of the western island, particularly along roadsides and stretches of undeveloped (southern) coastline. These patterns speak to how natural amenities that drive development pressure often correspond with ecologically sensitive areas - such as along pristine coastlines or interior bays - and highlights the strong influence that infrastructure networks have in facilitating emergent development.

Urban and tourism sectors also exhibit similar patterns when compared to the most suitable sites for agricultural use - highlighting a potential for conflict in the downtown core and portions of the suburban periphery. The distribution of this overlap suggests a shared interest in (sub)urban infill development - the potential for growth amidst the existing built-up area. Mutual priority of such sites may also suggest opportunities at the interface of those land uses such as rooftop farming and agritourism. Overlap between upper-percentile suitabilities for the two agricultural uses suggests that certain areas may accommodate mixed agricultural methods with soilless and outdoor farming. Lastly, mapped overlap between urban fabric and tourism depicts some areas of mutual priority in the west of the island and, most clearly, along the coast near the urban core. These apparent conflicts speak to the overlap of enabling conditions and development priorities for two built-up uses that serve distinct societal functions. This calls for well-targeted strategy balancing functions provided by the land use in terms of housing and services for the local population on one hand and revenue and employment produced by increased tourism capacity on the other.

3.4. Suitability agreement with spatial planning

Models predict highest probability for suitability within ‘most appropriate’ zone(s) in all cases except for urban fabric (and structural agriculture, for which such a zone is not clearly established) (Table 2).

Table 2
Matrix of mean suitability probabilities in each EOP zoning class (columns). Rightmost column depicts average scores for total area outside most appropriate zones. * indicates most appropriate zones for the land use(s) represented within each model.

	conservation / park area	urban / inner city	tourism	agriculture	rural	open land	industrial	all unplanned
conservation	94*	62	84	83	80	93	69	76
urban fabric	68	79*	82	67	76	64	49	68
tourism	35	42	49*	29	32	30	39	36
agriculture (conventional)	58	73	62	75*	73	61	60	64
agriculture (structural)	70	85	75	81	80	72	79	NA

All sectoral models predict higher suitabilities inside their most appropriate zones than the combined area beyond them, although average scores outside can still be deemed 'high' (>60%, per (McCloskey et al., 2011)) for all sectors besides tourism (rightmost column, Table 2).

The conservation model shows the most significant difference between scores inside and the average of the scores outside of its corresponding zone (17%, Table 2). This alignment is also reflected in the 'strong' positive correlation yielded by the point-biserial (Pearson's) analysis (Table 3). The average suitability of other zones for conservation generally reflects the extent of pre-existing development present. Suitabilities for conventional agriculture best correspond with the designated 'agricultural' zone, but are nearly as high in 'urban/inner-city' and 'rural' zones. The high prioritization of areas zoned 'urban' seems to align with experts' belief in the viability of the land use in more of a patchwork formation, amidst built-up area and close to where people live. The model for structural agriculture is exceptional in its identification of 'industrial' zones as highly suitable, suggesting that sites where industrial uses are discontinued could be uniquely attractive for this land use. The 'tourism' zone features the highest average suitability scores from the tourism sectoral model, a relationship also reflected by a medium-strength positive correlation between model and zoned area. The low average score for tourism zones may suggest that more land is presently designated for this use than is appropriate or, if total planned area is seen as desirable, that a delineation might be realized that better aligns with perceived suitability. The urban fabric model predicts highest average scores in areas planned for 'tourism', followed closely by 'urban/inner-city' and 'rural' zones. It is the only model exhibiting weak positive correlation with the corresponding 'potential zoned area' in the EOP. That areas planned for tourism are deemed the most suitable by the urban fabric model suggests that zoning law may be actively limiting the emergence of other built-up uses in these areas. It also speaks to the overlapping interests, particularly for high-end or luxury housing, between the two sectors, as evident in the previous analysis: People want to live where tourists want to stay.

4. Discussion

In this paper we developed a novel approach that coalesces and spatializes expert system understanding across various sectors, overcoming barriers traditionally posed by data scarcity through collaboration and explicit treatment of uncertainty. This method estimates land suitabilities for four land use sectors and identified locations of potential competition for land as well as alignment with prevailing spatial policies. The approach used has an applicability to other contexts and can serve to inform land use planning as well as as a base for exploratory models of land use change.

Table 3
Point-biserial correlations between suitability scores and most appropriate zones.

Land use	Correlation coefficient	t-factor	Deg. freedom
conservation	0.51 (strong)	42.14	4990
urban fabric	0.25 (small)	18.77	4994
tourism	0.37 (medium)	28.10	4974
agriculture (conventional)	0.50 (medium)	40.58	4997

4.1. *Incorporating uncertainty and diverse knowledges*

Systems mapping using Bayesian networks enabled us to perform land suitability assessment for several sectors due to the approach's capacity to account for uncertainty and non-linear influence of suitability factors. The probabilistic nature of BNs facilitated integration of disparate knowledge on land use from experts, enabling quantification and spatialization. Through their programming of conditional probability tables (Appendix D), experts were able to account for uncertainty inherent to the land use(s) in question as well as uncertainty in their representation (model structure, node definition and discretization, and in response to concerns about data precision and completeness). The approach does not distinguish between these two sources of uncertainty or address possible conflation of conditional probabilities with confidence in their veracity - a common quandary in Bayesian network interpretation (Marcot, 2017). Nevertheless, final models were found by stakeholders to be reasonable representations of respective land suitabilities, suggesting confidence in their predictive capacities regardless of probabilistic precision.

Conditional probabilities were wielded to different effect by the various expert groups: the conservation experts more often assigning highly modal (leptokurtic) probability distributions as opposed to the more well-distributed (platykurtic) distributions that predominated other groups' models. These differences are reflected in mapped outputs, where suitability likelihoods for conventional and structural agriculture, for example, range only from 36% to 84% and 51–89%, respectively, across the entire study area. Despite the uncertainty they convey, these results remain insightful in their depiction of the spatial arrangement of relative suitability likelihoods. The ability of this approach to accommodate sectors with high uncertainty in what conditions determine suitability is a crucial advantage, as land uses with the most uncertain dynamics are often those for which planners most desperately need spatial information, however imprecise.

The flexibility of the methodology allows for engagement with expert groups with vastly different approaches to the land suitability problem. Different economic sectors look at spatial issues in different ways, which can result in competing land use decisions (McCloskey et al., 2011). Capturing and representing a broad diversity of understandings and perspectives is necessary to account for land use interests across disparate sectors, a crucial endeavor when faced with questions of allocation amidst potential tradeoffs. The differences in perspectives on land suitability by different sectoral groups is readily apparent through variability in model structures and content but also in the underlying logic they apply. While asymmetry in groups' conceptualizations of suitability and nonuniformity in their probabilistic reasoning complicates direct comparison between sectors (a score of 60% may hold different meaning across groups), the similar format of the outcomes in terms of spatial scoring and the use of relative thresholds facilitated further analysis and meaningful findings despite this variety. This study does not incorporate the perspectives of a wider stakeholder base, focusing instead on the opinions of a few individuals identified for their expertise. Diverging views and values between different types of stakeholders, both expert and "non-expert", are known to contribute to land use conflicts through, for example, mismatches in preference and expectations (Brown et al., 2018; Kangas et al., 2022; Karimi and Hockings, 2018). This is a limitation that should be addressed by future research.

Much of the value of participatory BN methods lies in their ability to update human knowledge and insight through a co-learning process (Barbrook-Johnson and Penn, 2022; Celio et al., 2012; Voinov et al., 2016). In addition, the objective of planning support is likely to be achieved only with buy-in or uptake by stakeholders (Voinov and Bousquet, 2010). The visual nature of BNs offers advantages as a comprehensible and flexible tool for active involvement with stakeholders (Chen and Pollino, 2012; Marcot and Penman, 2019). In a context of siloed and occasionally conflicting sectors it is envisaged that symmetrical procedures and assessments that are less value-based will help produce evidence more conducive to, if not collaboration, at least transparency in spatial planning. The receptiveness of the approach to diverse and incomplete understandings and data also speaks to the potential applicability of the approach in diverse contexts beyond the case presented here.

4.2. Operating with incomplete or missing data

One of the ways this methodology sought to navigate the constraints of data scarcity was by bringing the question of data availability to the fore during modeling workshops and by integrating dataset validation into the iterative model validation process. Thus, expert models were constructed and parameterized with a continuous acknowledgement of data limitations. During modeling, proxy variables were used to represent the (joint) influences of factors without representative datasets. Examples include the conservation group's use of observation data and flora richness maps in place of more detailed datasets on species ranges and representation of visitor demand via density of geotagged social media photos. The uncertainty introduced by such proxies and other perceived limitations were directly accounted for through values assigned to conditional probability tables (Marcot et al., 2006). Input data, once assembled, was reviewed alongside preliminary model behavior during validation so that parameter values could be adjusted to reflect data realities. This is reflected by sensitivity analysis (Appendix E), which showed that target nodes of the validated models were typically most sensitive to variables that we consider robust as they were produced from precise spatial data with robust spatial analysis that minimize uncertainty.

The concept of validity in the context of expert-elicited causal models is not absolute but a question of additive strength (Pitchforth and Mengersen, 2013). As such, iterative validation in this vain has been touted as an appropriate means to validate expert-elicited Bayesian networks (Catenacci and Giupponi, 2013; Celio et al., 2012). In this specific, land planning context, it served the vital function of facilitating consensus over unfamiliar spatial datasets and the 'folding-in' of learning generated throughout the procedure into the process and the products of the BNs, an advantage also highlighted by Barbrook-Johnson and Penn (2022). The transferability of these sectoral models, as parameterized, to other contexts is likely limited by their having been adapted to local data realities in this way. Nevertheless, the suitability factors and model structures themselves can help contribute to a growing understanding of these land uses beyond the studied area. For example, while their relative influence may differ, spatial drivers such as viewshed favorability, coastal proximity, and infrastructure access identified in this case may be extensible to land suitability for tourism in other small island developing states or the wider Caribbean region.

As detailed above, the 35 datasets used as model inputs were assembled with varying degrees of expert involvement. Many were assembled independently, with experts' roles limited to ensuring the information depicted matched intended definitions for variables. Experts, in such a case, might simply refine their discretization of node states for a continuous variable such as 'distance to coastline' or adjust their definition of what constitutes a 'cultural heritage site' upon seeing this information depicted visually and reviewing the impacts on modeled outcomes. In other cases, expert knowledge was engaged directly to produce novel datasets, such as the 'neighborhood safety indices' or 'noise nuisance' maps. In this way, the approach diverges from and expands upon the few existing applications of Bayesian networks in land use (change) evaluations (Andriatsitohaina et al., 2020; Celio et al., 2014; Celio and Grêt-Regamey, 2016; McCloskey et al., 2011; Meyer et al., 2014; Nascimento et al., 2020; Stritih et al., 2020). Shaping (and provision) of input data by stakeholders may provide an additional channel by which participant beliefs are eventually conveyed in model outputs, an effect which, although unintended, complements the aim of the exercise. In this way, this methodology could be applied in contexts of even more extreme data shortage, where missing empirical spatial datasets might be progressively substituted with citizen-science-based depictions of spatial information. Sensitivity analysis of fully elicited models (as in Appendix E) can help identify key knowledge gaps and nodes for whom additional emphasis should be placed on collecting robust data (Chen and Pollino, 2012; Pollino and Henderson, 2010).

4.3. Supporting spatial planning

The application in Curaçao clearly illustrates the utility of this approach for informing planning and near-term management decisions in a context of limited resources and constrained capacity. The results provide knowledge over individual land use priorities and the underlying factors that might be leveraged to promote or limit their emergence. While suitability is one input to spatial planning processes, spatial planners must also interpret and translate societal objectives into their delineations of prospective land use (Hersperger et al., 2018). The modeled results of our analysis connote 'suitability', an area's conduciveness to emergence of a given land use(s), but not necessarily *desirability*. This methodology does not address demand directly, but it does offer insight into what opportunities exist and what sacrifices might be incurred given mis- or undermanagement of finite land resources. While high probabilities may not suggest a 'desired outcome' for a specific site, they at least indicate the importance of engaging with stakeholders from that sector when planning possible futures for that site. By bringing more sectors into the fold, decision-makers get more space to discern and act upon the results they deem meaningful.

Information on locations of potential competition for land could help planners optimize land use decisions and limit tradeoffs. High suitability for multiple land uses is identified as one of the root causes of land use conflict (Wang et al., 2012; Zong et al., 2022; Zou et al., 2019). At the same time, high suitability for multiple sectors may also suggest complementarity. A specific example for Curaçao are areas exhibiting high suitability for both tourism and conservation uses, coincident in several instances with cultural heritage sites, which highlights the possibility for land uses that both conserve the natural functioning or human history of these sites while promoting sustainable access to the areas. Some sectors are more constrained and highlighting areas of potential conflict can help protect the land interests of those with less available suitable land or where conversions cannot be easily reversed. On Curaçao, this may apply to conventional agriculture, which features the second lowest median suitability probability across the entire island, and for whom conversion to more intensive uses (i.e. tourism or urban development) can preclude dedicated agricultural use for the foreseeable future (Cobbinah and Aboagye, 2017; Martellozzo et al., 2018). Given demand/political will, areas of high suitability exhibiting no conflict might be seen as 'low resistance' areas where rezoning or other intervention might facilitate desired levels of land use transition/development.

Results from the analysis of agreement between modeled suitability and prevailing spatial policy provided insight into how expert expectations align with desired land use configurations, to the extent this is reflected in current regulation. This analysis allowed for an exploration into where development pressures are anticipated that do not conform to planned uses. Insight is offered, for example, into where zoning may constrain (favorably or unfavorably) the emergence of land uses from the modeled sectors. The outcomes of such an analysis can also highlight where permitted uses within existing zones might be expanded to accommodate apparent synergies, for example, allowing and encouraging more (structural) agricultural uses within the urban zones.

4.4. Providing a basis for exploration of land use change

In addition to its apparent utility for informing near-term spatial planning and resource management decisions, the methodology outlined in this paper also exhibits potential to drive more advanced studies to support planning, such as forward-looking studies of land use configurations under future scenarios. Modelling land use conditions under different, uncertain, futures can provide early warning and enable evaluation of environmental management and policies in order to better addresssustainability issues (Verburg et al., 2016). Many such tools adopt a spatial allocation procedure with land suitability as one key determinant. Given the complexity and multi-dimensionality of the allocation problem, many models of land use change rely on statistical/inductive approaches, such as econometric analysis, to infer a proxy for land suitability. Such approaches assume that the factors that shaped past or current land use patterns retain the same relevance under future conditions (Verburg et al., 2019, 2002). The case from this study evinces the limitations of such an assumption, considering the many inflection points in Curaçao's dynamic land use history, such as the construction of the refinery and rapid subsequent suburbanization of Willemstad. Suitability characterizations learned entirely from data, via regression analysis or other approaches, also depend on researcher expertise or recommendations from literature to assume a set of (potentially) influential variables. In distinctive and understudied contexts, such as small island developing states, such practices may result in omission of critical explanatory factors of special local relevance - reducing accuracy and salience for local decision-makers (Bürgi et al., 2022). Stakeholder knowledge can act as a vital complement to these approaches, helping to ground modelling assumptions in lived understandings of local systems. Process-based expert depictions of land suitability for numerous sectors, as generated through the present methodology, are especially viable for incorporation into future scenario studies as they easily integrate changing datasets. As future conditions emerge, predictions of suitability will respond dynamically.

5. Conclusion

We present an iterative process of stakeholder elicitation and Bayesian network modelling that can generate, for different economic sectors, maps of land suitability for development of that sector. The application showed that this method is capable of addressing uncertainty linked to the factors driving suitability and including knowledge of a range of different stakeholders in a consistent manner that allows for suitability comparison. We have illustrated the utility of such information for mapping potential conflict between land uses (for example, between tourism and conservation along bays and roadsides of western Curaçao), to quantify alignment with established spatial policy, and to inform land use planning either directly or as input to more advanced land use modelling studies. In spite of limitations related to external validation and difficulties of stakeholder engagement, the approach proves viable in contexts of low data availability and sparsely researched environments where drivers of land suitability are unknown and uncertainty pervades.

CRediT authorship contribution statement

Rex Steward: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Peter H. Verburg:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Pierre Chopin:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Peter Verburg reports financial support was provided by Nederlandse Organisatie voor Wetenschappelijk Onderzoek Utrecht.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103733.

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