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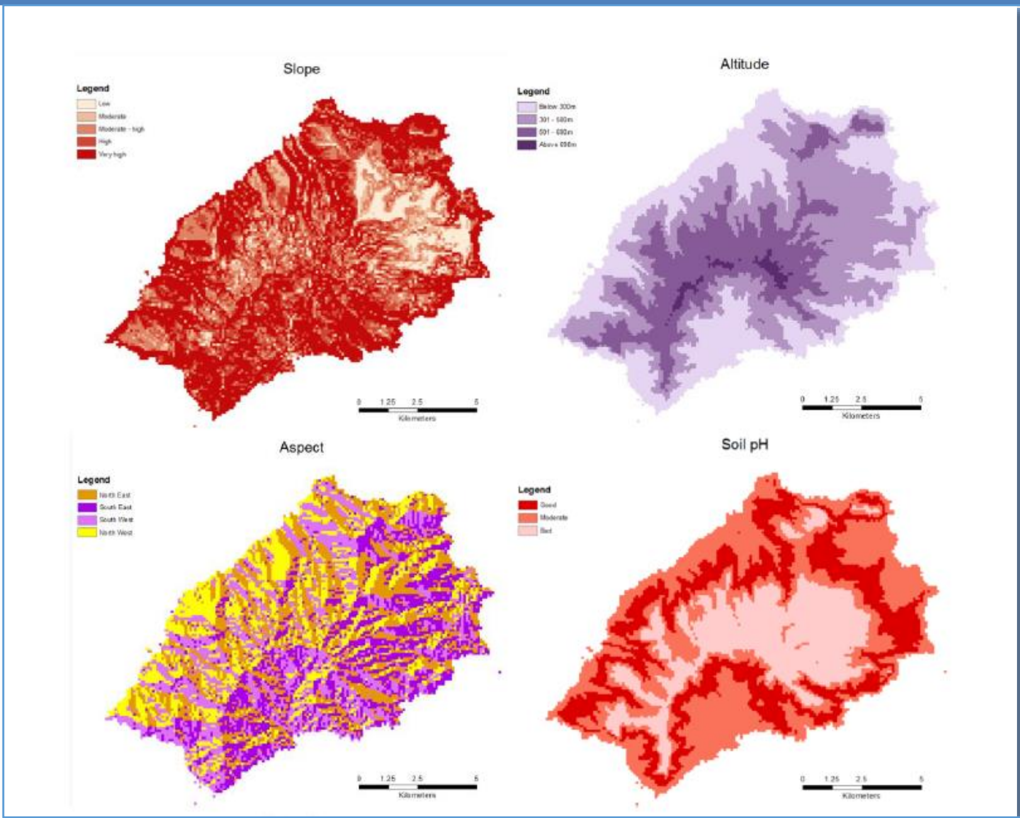
JNCC
Joint Nature Conservation Committee

South Atlantic Natural Capital Assessment; Modelling St Helena's Natural Capital



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Non-technical summary

Key messages

- St Helena's natural capital underpins and shapes the benefits that people derive from its land use and habitats. This includes both terrestrial and marine habitats.
- Modelling natural capital using a spatial approach allows the places where those benefits might be highest to be identified.
- There are opportunities and policy drivers to expand the production of different land uses including agriculture, coffee and forestry. Natural capital assessment can help to identify where those opportunities are greater.
- These opportunities will have a range of ecosystem service co-benefits. Understanding where these occur can help to inform better land use planning.
- Natural capital modelling can also inform decisions about natural habitat restoration and creation.

What is natural capital?

Natural capital refers to the stock and condition of the natural environment. This includes both biotic habitats and abiotic elements such as landform. The term reflects human relationships with nature and its role as the underpinning of our society and economy. St Helena's natural capital is the stock of natural resources including its habitats, geology, soils, air, water and living organisms.

Why is natural capital important to St Helena?

St Helena's natural capital assets underpin the ecosystem services that provide a range of benefits to the people of St Helena (Figure S1). Sustainable use of natural capital is important to maintain St Helena's prosperity into the future. If it is degraded then the ability to provide food, timber, firewood and supply water will decline or become more reliant on man-made inputs. Natural capital contributes to the control of water flows and erosion, pollination, and places for recreation. The unique characteristics of St Helena that attracts tourists also rely on its natural capital. Maintaining healthy natural capital will help St Helena to be more resilient to future changes including increasing demands for food, materials and water, or events such as droughts.

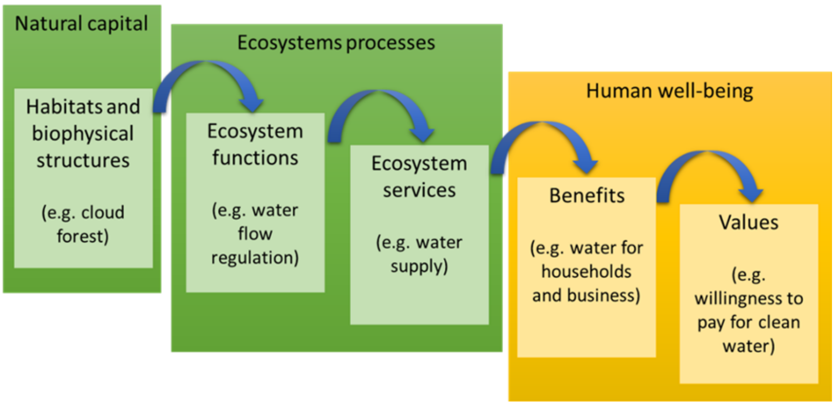


Figure S1 How does natural capital lead to human benefits?

What is a Bayesian network?

A Bayesian network describes the relationship between different parts of a system using a series of interconnected nodes (**Error! Reference source not found.**). These relationships are expressed in t erms of probabilities. The approach is very flexible as it can use a variety of different data types

We use a Bayesian network to model how St Helena's nature capital contributes to different benefits including food production (crops, livestock, coffee and honey), timber, firewood, water supply, flood and erosion prevention, and recreation. The Bayesian network represents the links between different elements of natural capital and the ecosystem processes that contribute to ecosystem services.

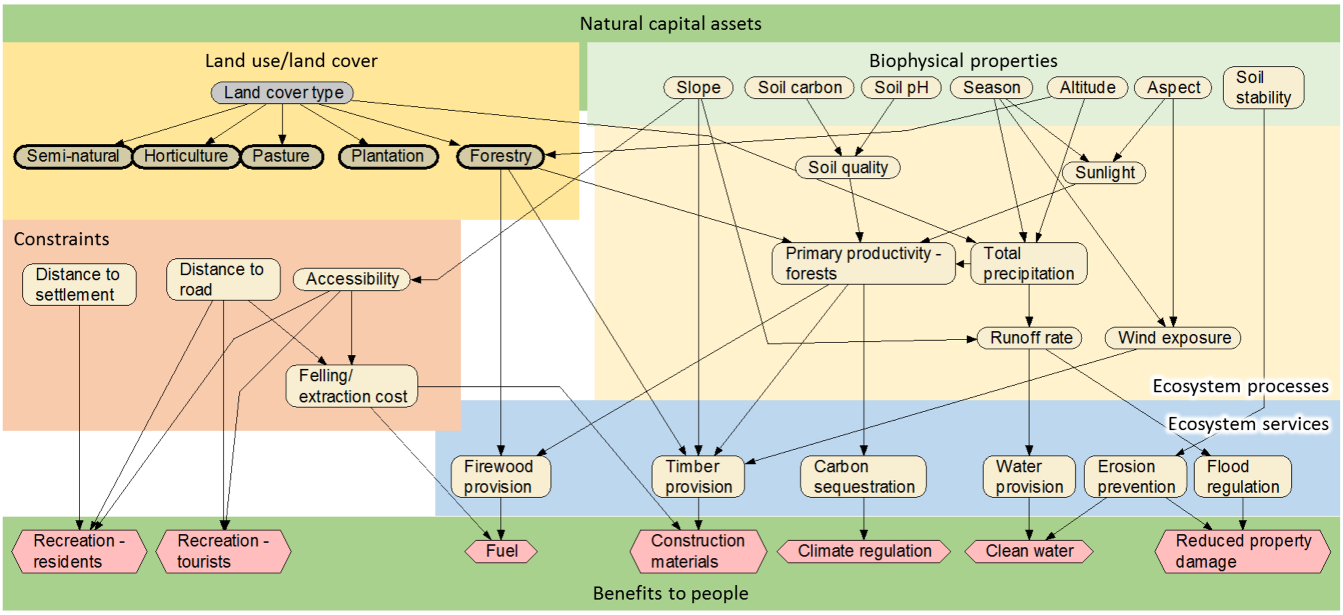


Figure S2 Simplified network diagram for the forest sector

What input data do we use?

The key input into the Bayesian network is the habitat map of St Helena[1]. This was simplified to include the main natural and introduced habitats and important land uses (Figure S3).

The model includes other natural capital assets including soil quality, slope, altitude, precipitation. These can act to either enhance or constrain the ability of habitats and land uses to deliver different ecosystem services. Each of these inputs was map based. This allowed us to evaluate the Bayesian network spatially across St Helena and to present the results as maps.

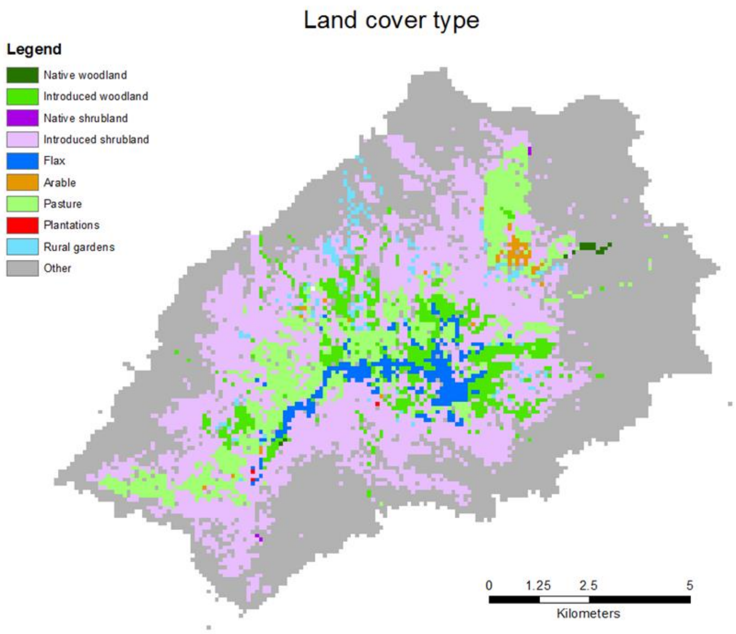


Figure S3 Land cover map of St Helena

What did we find?

The Bayesian network evaluates the ecosystem services associated with the current land uses on St Helena. The provision of food, timber and firewood reflect the locations of those land uses, but are also enhanced or constrained by other aspects of natural capital. Each land use contributes to a wider range of ecosystem services. The potential for those ecosystem services depends on the intensity of land use and the characteristics of the where it occurs. For example, provision of clean water and flood risk reduction are higher where the land uses such as forestry are able to slow down the flow of water and where slope is not too high. Pollination relies on diverse habitats.

[1] https://data.saeri.org/saeri_webgis/lizmap/www/index.php/view/map/?repository=01sh&project=saint_helena_web

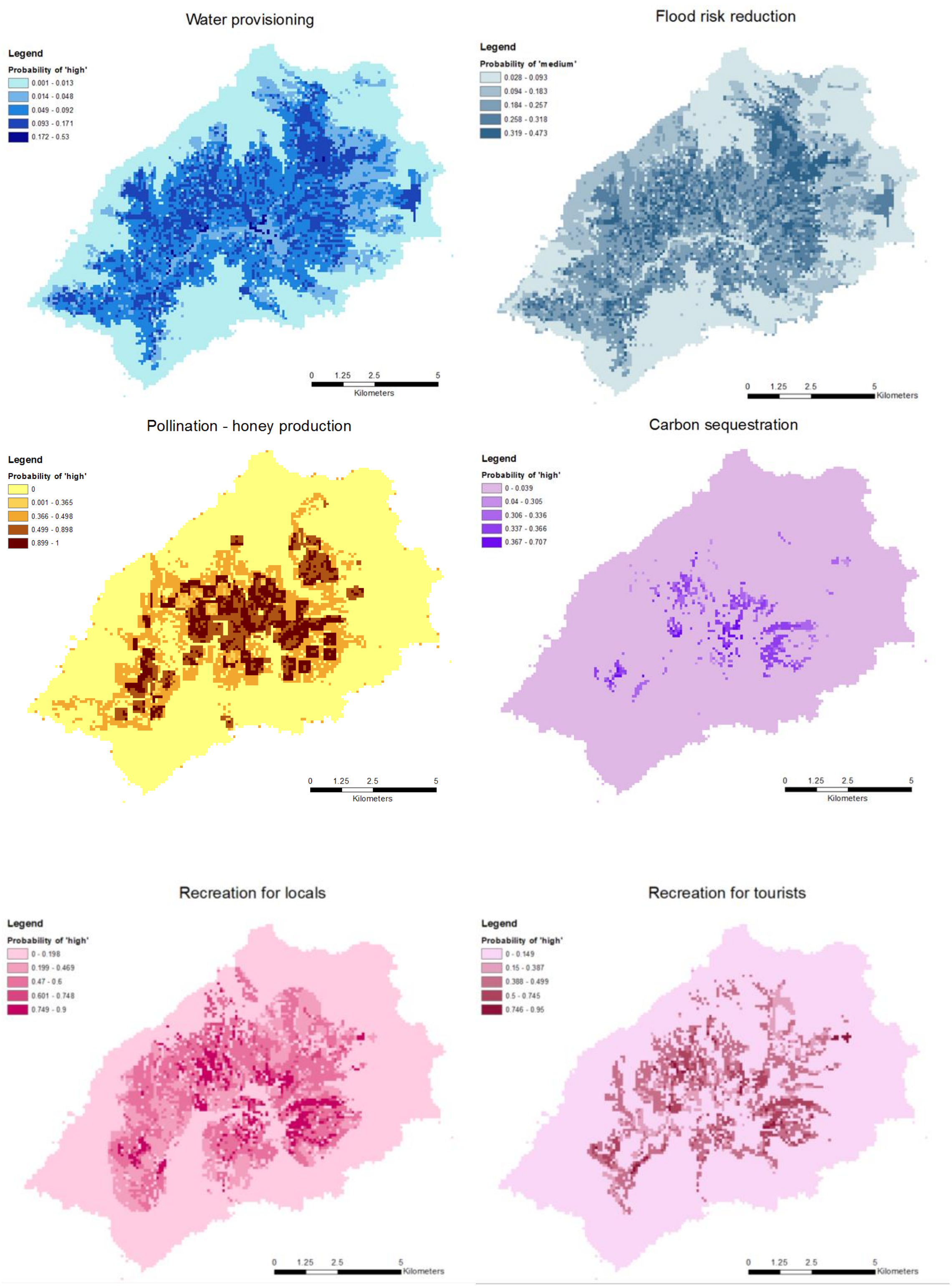


Figure S4 Ecosystem service outputs from the Bayesian network, darker colours indicate greater service potential

Using the Bayesian network to evaluate future land use

The model also explored the land use implications of a range of scenarios for St Helena's future. Common themes involved expanding production of food and other materials (to reduce import dependence or to increase exports), and to continue removing flax. Alternative land uses included:

- Expansion of forestry for timber and fuel
- Expansion of food production: horticulture, coffee and honey

- Removal of flax: replace with timber or native woodland

The associated ecosystem services of these changes such as carbon sequestration, water supply and recreation can also be evaluated

The following maps illustrate opportunities for expansion of biofuel (including energy crops on pasture), timber, horticulture and coffee. The key constraints were slope, accessibility and avoiding loss of native habitats and horticultural land

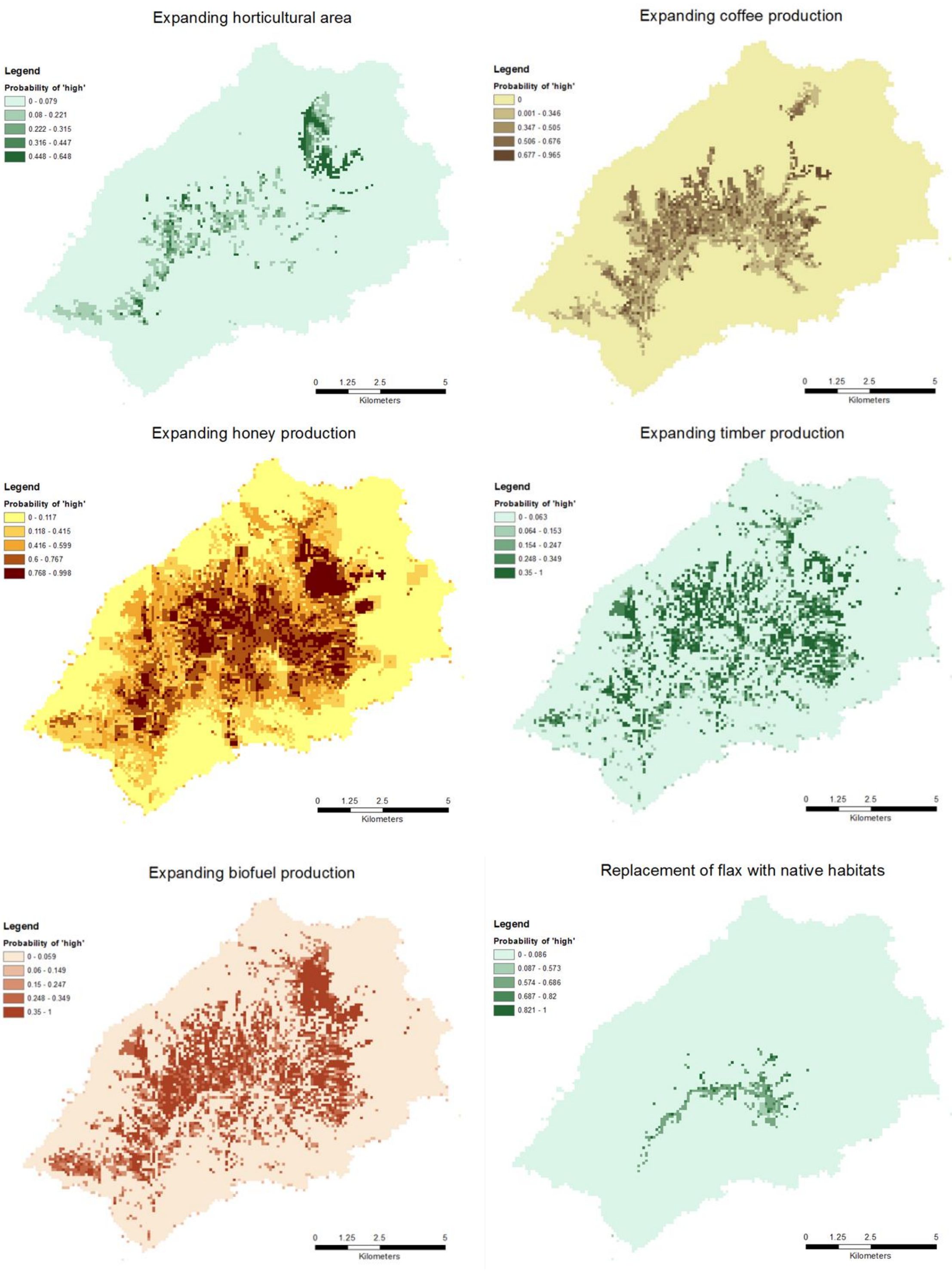


Figure S5 Opportunity maps for future land use change

1. Introduction

This study was commissioned by the South Atlantic Environmental Research Institute (SAERI) to develop a land-use model for St Helena. The findings contribute evidence to a programme of natural capital assessment (NCA) being implemented by the UK Joint Nature Conservation Committee (JNCC) and conducted by the South Atlantic Environmental Research Institute (SAERI) in the UK South Atlantic Overseas Territories. Funded by the Foreign and Commonwealth Office (FCO) managed Conflict, Stability and Security Fund (CSSF), the work sits under its Environmental Resilience programme which includes objectives to integrate natural capital considerations into economic and social development planning.

A consultation workshop held on St Helena in January 2018, followed by a smaller Advisory Group meeting, resulted in priority areas being identified by on-island key stakeholders for further study. Land use, and associated natural capital, was one of these priority areas. Particular thanks go to the St Helena Advisory Group, St Helena Government, and the many stakeholders who made major contributions to our understanding of St Helena's natural capital. Without their input, this work would not have been possible.

St Helena is characterised by spectacular landscapes and incredibly rich biodiversity, with a third of the endemic species found on British territory. Of the 1000 invertebrate species found on the island, over 400 are endemic, this outnumbers the combined number of endemic invertebrates across the rest of the UK and the Overseas Territories (Peters, 2011; Churchyard et al., 2014). However, the isolation that has led to this species richness also makes St Helena vulnerable to invasive species whether intentionally or accidentally introduced. These species, the habitats they form and rely on, and the landscapes in which they are found are part of St Helena's natural capital.

Natural capital is the stock and condition of the natural environment, including both biotic and abiotic elements. The term reflects human relationships with nature and its contribution as the underpinning of our society and economy. The sustainable use of natural capital is key to ensuring St Helena's future economic prosperity and the well-being of its people. Understanding how different aspects of natural capital interact to provide ecosystem service benefits allows better decision making about how to use that natural capital and what the impacts of land use policy and management may be.

This report presents the findings of a study that modelled St Helena's natural capital including an exploration of different future development scenarios. The model is not intended to provide the 'right' answers to questions of land use and environmental management. Instead, it aims to improve understanding of natural capital linkages and inform better decision making. In particular there may be important trade-offs or synergies between different natural capital benefits that need to be identified and considered. We use a spatial approach that maps natural capital inputs and outputs which can be readily interpreted, and compared to stakeholder knowledge of land use on St Helena. The model is a simplification of reality and is based on a limited set of inputs that describe St Helena's natural capital. For example, the model outputs do not reflect institutional factors such as land ownership and tenure, or designated areas such as National Conservation Areas[2]. The model also focuses on the vegetated terrestrial habitats within the 'green heart' of the island.

In the next section we discuss the natural capital framework used as the basis for our model structure. We then describe the Bayesian network approach used to model St Helena's natural capital, the data sources used and the development of the model. Section 4 presents the results of the model for

[2] National Conservation Areas are split into four categories: National Parks; Nature Reserves; Important Wirebird Areas and Historic Conservation Areas, see http://www.sainthelena.gov.sh/national-conservation-areas/

current land use of St Helena. This includes the provision of a number of different ecosystem services including food, water, flood regulation, pollination, carbon sequestration, and recreation. We then consider a number of future scenarios developed by stakeholders on St Helena and identify the land use changes that these might imply. These include expanding food production for both local consumption (horticulture and honey) and for export (coffee and honey), expanding forestry for timber and biofuel, and replacing invasive flax. We evaluate the ecosystem impacts of these scenarios. Finally, we summarise the model results, discuss the limitations of the approach and describe how the model can be used in future.

2. Approach

In this section we set out the underlying framework and approach for modelling St Helena's natural capital. We adopt the ecosystem services cascade (Haynes-Young and Potschin, 2009) as a conceptual model which forms the underlying structure and logic for the natural capital model. The model itself is developed using a Bayesian network.

2.1. The ecosystem services cascade

This project aimed to model the connections between St Helena's natural capital, the ecosystem functions and processes it underpins, and the ecosystem services that are then delivered to the people of St Helena. This can be conceptualised in terms of the ecosystem services cascade (Haynes-Young and Potschin, 2009) as illustrated in Figure 1. The cascade has been adapted here to explicitly include natural capital, this includes habitats and biophysical structures or characteristics (both biotic and abiotic). Natural capital can be described in either quantitative or qualitative terms, or both. For example, habitats can be measured in terms of both area (quantitative) and condition (qualitative), both of these aspects will contribute to the types and amounts of subsequent ecosystem functions and processes that a natural capital asset can support. From a policy and management perspective it is also important to know how extent and condition contribute to ecosystem processes[3].

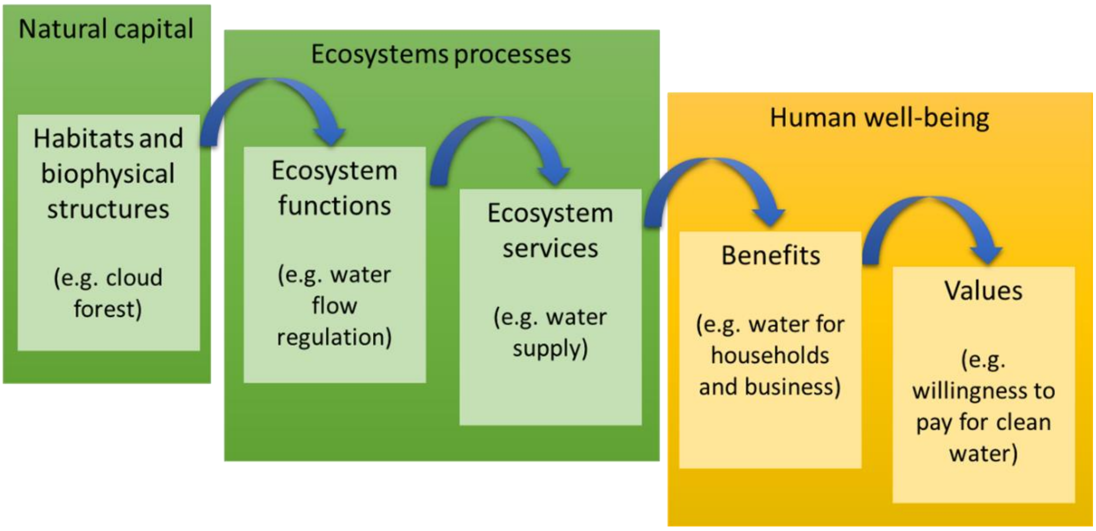


Figure 1 Natural capital and the ecosystem services cascade (adapted form Haynes-Young and Potschin, 2009)

The example set out in Figure 1 considers 'cloud forest' as the natural capital asset, this habitat is relevant to St Helena given the contribution of mist to overall precipitation. We can conceive of the natural capital asset condition in terms of the composition of the vegetation and its suitability for mist capture. Other relevant natural capital assets, or states of nature, could include altitude (reflecting where mist occurs), soil type or condition, and slope. These will contribute to processes that control water flow and chemical condition, which in turn lead to the ecosystem service of water supply. Finally, that service provides benefits to people and businesses on St Helena that can be valued either through the payments made to Connect (the St Helena utility company), or a broader measure such as willingness to pay for clean water.

[3] The spatial approach we adopt in this study is based on 1 hectare pixels of a habitat and land use map of St Helena. Consequently, the type and condition of natural capital assets are more relevant, as extent is captured at the pixel level.

The aim of this project is to model this natural capital and ecosystem services cascade across a range of habitats including interactions with other states of natural capital. As such, the cascade provides the logical structure for the model we develop.

2.2. Bayesian networks

Bayesian networks (BNs), also called Bayesian belief networks (BBNs), belief networks or causal probabilistic networks, have been applied across a wide range of disciplines including medicine, finance, industrial diagnosis, as well as an increasing number of environmental and natural resource issues. BNs can be used for both decision support and as investigative tool to explore how systems operate without the need to know the full functional relationships or the associated data.

BNs have been widely applied in numerous environmental studies including fisheries (Kuikka et al., 1999; Lee and Rieman, 1997; Pollino et al., 2007); forest restoration (Haas et al., 1994); climate change (Gu et al., 1996; Kuikka and Varis, 1997); habitat restoration (Rieman et al., 2001); and watershed management (Hamilton et al. 2007; Ames et al., 2005; Borsuk et al., 2004; Bromley et al., 2005; Henriksen et al., 2004). The benefit of using BBNs in natural capital management is their usefulness for predicting the links between management practices and ecosystem reactions (Clark et al., 2001; Borsuk et al., 2004), while they can also deal with a large number of interconnected data and integrate different types of variables (e.g. environmental, economic, social and physical variables) or knowledge from diverse sources (Pearl, 1988; Bromley et al., 2005).

BNs represent interactions between a range of variables, which may include uncertain quantities as a directed acyclic graph (Figure 2a) which is formed by a series of interconnected nodes that link actions to outcomes (Barton et al., 2008; Pollino et al., 2007; Borsuk et al., 2004). The nodes represent the variables of the system, while the linkages among them indicate direct causal dependencies (Pollino et al., 2007); these cannot form a closed loop as shown in Figure 2b (Bromley et al., 2005). Those nodes that do not have any conditional dependencies are called 'parent' nodes (e.g. A and C in Figure 2) and represent input variables, while those that are conditionally dependent on at least one other are called 'child' nodes(e.g. B and D in Figure 2). Nodes without child nodes constitute the output of the system (e.g. D in Figure 2).

The strengths of the causal relationships among the system variables are quantified by conditional probabilities. These are defined by a set of conditional probability tables (CPTs) that specify the probability of each variable having a particular 'state' considering every possible combination of states of the parent nodes linked to it (Kjærulff and Madsen, 2005; Kragt, 2009; Pollino et al., 2007; Bromley et al., 2005). The state of the parent nodes is determined by a marginal (or unconditional) distribution of probabilities (Pollino et al., 2007; Borsuk et al., 2004) set by the operator. Variables can be determined either as discrete or continuous (Cain, 2001); with the state of each described by either a numerical value, a verbal description, or even a true or false statement (Bromley et al., 2005). The probability values in the CPTs can be based on empirical observations, or our beliefs, about the relationship between nodes, e.g. elicited from literature reviews, stakeholder consultation or expert judgement (Pollino et al., 2007). BNs also allow deterministic relationships to be specified between some nodes if those are known, this allows the integration of other modelling approaches into BNs. Consequently, BNs are very flexible in terms of data requirements, and this makes them well suited to modelling complex socio-ecological systems such as those involving natural capital and ecosystem services. The flexibility of inputs means that knowledge from local stakeholders and indigenous people can by readily incorporated making this a good type of modelling approach for working with people on the ground. Both the structure of the BN and the values in the CPTs, both of which can be changed and updated to reflect such knowledge.

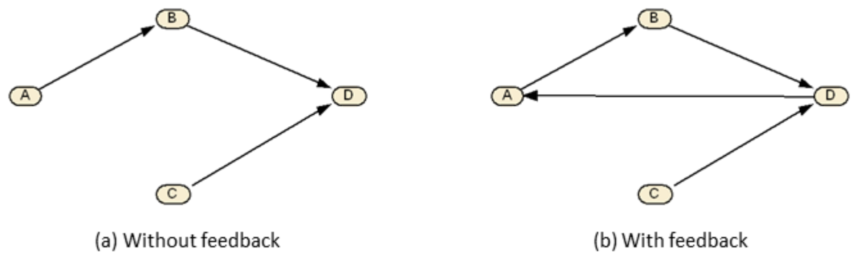


Figure 2 Directed acyclic diagram, without (a) and with (b) feedback

Figure 3 illustrates a simple BN of surface water flow, this is determined by two parent nodes: rainfall (i.e. the input of water into the system) and slope (i.e. the speed that it will flow). Each of the nodes has three potential states: high, medium or low. These states need not be linked to specific definitions such as the actual amount of rainfall, actual gradient or volume of flow. This would allow the model to be applied in different contexts where these quantities might vary. An example of the associated CPT for surface flow is presented in Figure 4. There are no CPTs for 'Rainfall' and 'Slope' as these are parent nodes, the states of these nodes can be selected by the user, or based on observed data.

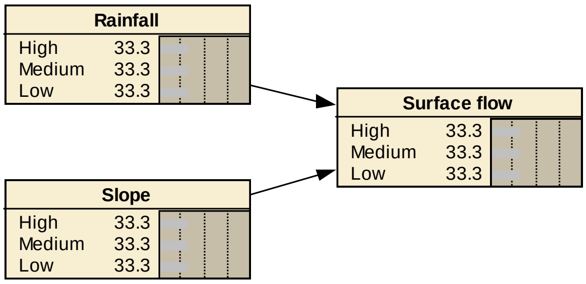


Figure 3 Example of a simple Bayesian network

The CPT represents all combinations of the states that the parent nodes can take, and how these then relate to the possible states of the child node. There is no predetermined way of ordering the parent nodes in the CPT. However, in our simple example 'Rainfall' is placed first as logically it is more important parent node, i.e. without input of water there would be no surface flow regardless of the slope.

Rainfall	Slope	Surface flow High	Surface flow Medium	Surface flow Low
High	High	100	0	0
High	Medium	80	20	0
High	Low	60	40	0
Medium	High	80	20	0
Medium	Medium	60	40	0
Medium	Low	40	40	20
Low	High	0	40	60
Low	Medium	0	20	80
Low	Low	0	0	100

Figure 4 Example of a conditional probability table

An important point with BNs is the models will provide the probabilities of each of the states of the child nodes occurring, rather than simply identifying the most probable state. This demonstrates the level of uncertainty about different outcomes, such as whether a particular state is much more likely than others, or, whether there is little difference in likelihood. This may create difficulties in interpretation but is arguably a useful feature of the approach. We return to this issue in the presentation of the BN results.

There are a number of advantages and disadvantages of the BN approach to consider, these are summarised in Table 1.

Table 1 Advantages and disadvantages of Bayesian networks

Advantages	Disadvantages
• Transparent representation of causal relationship between variables • Use of variety of input data – qualitative and quantitative information can be included based on empirical data, known functional relationship, stakeholder engagement or expert opinion • Representation of uncertainty –probabilistic nature so can reflect uncertainty • Can handle missing observations – expert knowledge or opinion can be used to fill data gaps • Structural and parameter learning – the process of developing BNs allows users to develop their understanding of how the system works • New evidence can be incorporated – as new evidence or knowledge becomes available it can added to BNs relatively easily as the structure of the model is clear and points of influence readily identifiable	• Structure requires agreement about system structures and influences – whilst the opportunity for group learning can be a strength of BNs • Difficult to define probability values with expert opinion – defining probabilities may not be easy particularly where underlying functional relationship are not well understood or are disputed • Lack of continuous data representation – BNs use variables with discrete states or levels, whereas continuous values may be more appropriate • No feedback loops – BNs cannot include feedback loops, this can be address by setting up multiple models and working iteratively • Potential 'black box' – although the structure and relationships in BNs is transparent, the underlying probabilities may be less so for users

3. Developing a Bayesian network of St Helena's natural capital

In this section we discuss the development of the BN for St Helena. We begin by describing the process we used to develop the network structure and how this was revised using a variety of data sources to reflect the natural capital and ecosystem processes relevant to St Helena. The input data sources are then described and illustrated.

3.1. Structure

An initial network was developed by members of the wider South Atlantic Natural Capital project during July 2018. This mapped out the linkages from land cover type and biophysical characteristics through ecosystem processes to final ecosystem services and is illustrated in Figure 5. As this is an initial network, not the final model, we will not discuss it in detail. The key points to note are that land cover type is a main input, with a distinction made between modified and semi-natural. Modified land cover in this iteration of the network refers to land that is actively managed for production such as timber, firewood or agriculture. Semi-natural includes both native species and non-natives that are not managed, i.e. they function in a similar way to natural habitats[4].

Land cover types then interact with biophysical characteristics including soil type, aspect and altitude as inputs into primary productivity, i.e. the quantity of biomass produced for a land cover patch given those characteristics. Slope is also included as a biophysical characteristic, but its main impacts relate to water flow, timber production and accessibility to allow timber or firewood extraction.

Primary biodiversity, defined by the 'naturalness' of land cover (i.e. more natural habitats are expected to have higher biodiversity, and landscape biodiversity, the diversity of surrounding habitats, are identified as drivers of pollination). In turn, pollination is key to coffee and honey production. Primary biodiversity is also linked to potential genetic and medical resources.

The next stages in the network reflect ecosystem services including food, timber, firewood and water provisioning; and regulating services including carbon sequestration, flood regulation and pollination. These are then followed by specific benefits, e.g. timber provides construction materials, food provision can be vegetables or meat. The lowest part of the network diagram contains constraints on the output in terms of costs that will affect the value of the benefits.

The network was transcribed into the Netica Bayesian networking package[5]. This was followed by an iterative process of network restructuring and parameterisation (i.e. completion of CPTs). A key element of this was identifying the relevant input datasets that can inform the natural capital asset nodes, these are described in the following section.

Data and knowledge on the network relationships was also identified and scrutinised. For example, the initial network includes a temperature node, this is influenced by altitude. Climate records for St Helena[6] and observations from DPLUS051 project (Sansom et al., 2018) were analysed to determine the relationship between altitude and temperature. Higher temperatures were observed at lower altitudes (e.g. Jamestown), but there was less variation at higher altitudes. However, as the habitats of interest occur at higher altitudes, and the overall variation in temperature was not considered as a limiting factor on ecosystem functioning, it was decided that temperature was not an important factor in the network. Consequently, it was not included in later iterations.

[4] The distinction between 'modified' and 'semi-natural' is removed in the final network (see Annex 1).

[5] Produced by the Norsys Software Corp https://www.norsys.com/netica.html. There are a number of BN software packages available. Netica was used initially as it has a relatively straightforward user interface.

[6] http://www.sainthelena.gov.sh/wp-content/uploads/2018/07/Climate-July-2018.xlsx

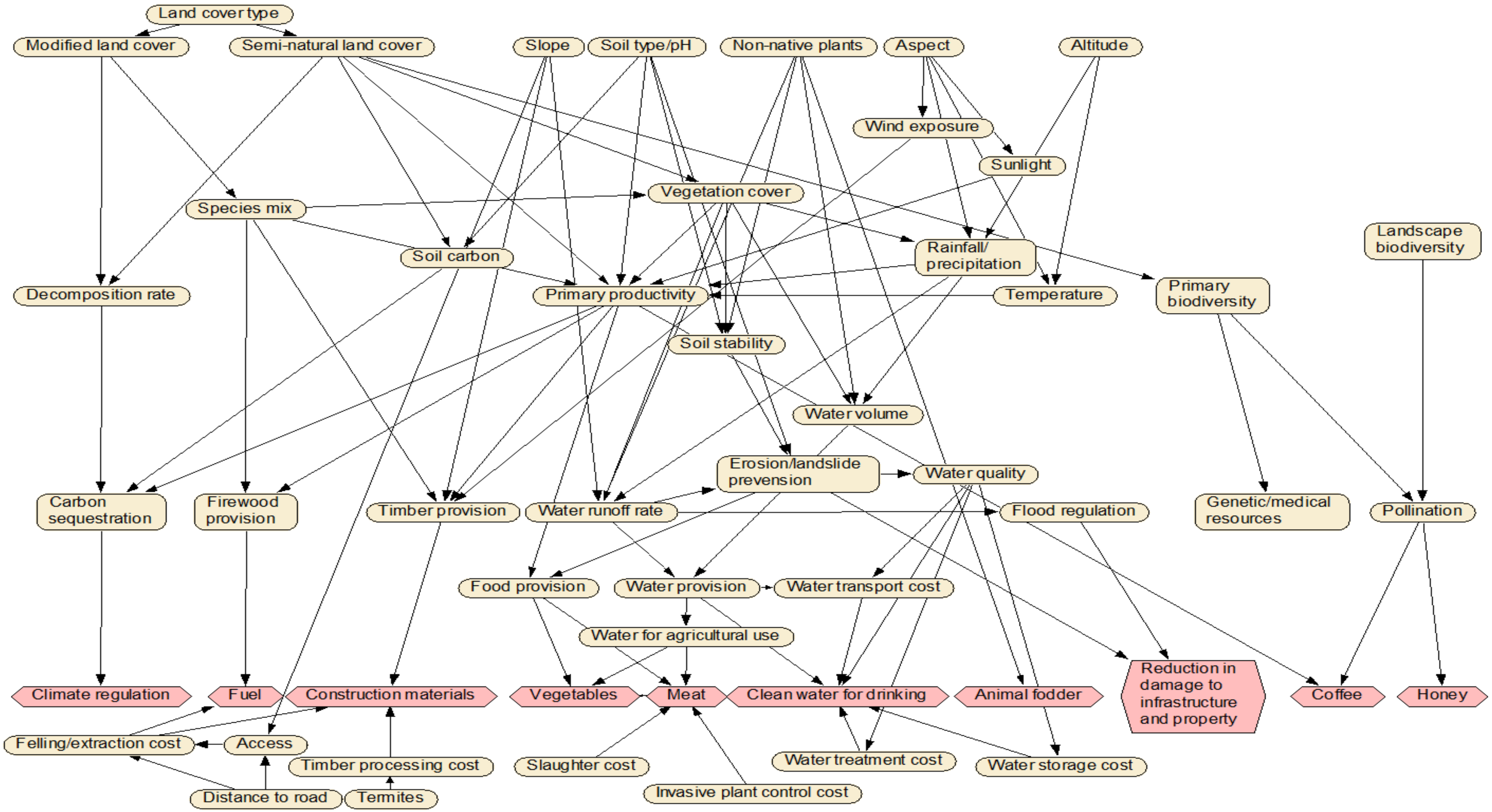


Figure 5 Initial network diagram for St Helena’s natural capital

Altitude is important for precipitation. The DPLUS051 project estimated that mist forms around 50% of St Helena's precipitation and this is captured by vegetation above an altitude of 690m. Altitudes above 500m were also noted as being better for timber production (forestry workshop notes). We used these altitude levels to define the states of the altitude node, rather than regular intervals or qualitative states (e.g. high, medium, low) as they reflect biophysical relationships of importance in the model. Mist capture is also related to vegetation type, with an assumption made that woodland habitats (semi-natural and introduced) provide a high level of capture, with shrubland (semi-natural and introduced) providing a medium level, where these habitats are above 690m. All other habitats provide a low level.

Climate data on sunlight, rainfall and wind[7] were also analysed to determine if there were any season variations. The monthly deviations of those factors from annual mean values are illustrated in Figure 6. This indicates a two-season pattern with more sunlight, higher temperature and lower wind speed between January and June or July. In contrast, there is less rainfall between September and February, with March to August be typically wetter with the exception of May. These observations suggest that nodes reflecting month and season could be added to the network to allow some the impact of season to be assessed if desired. The model can be also reflect 'annual average' conditions, this option is used for our analysis.

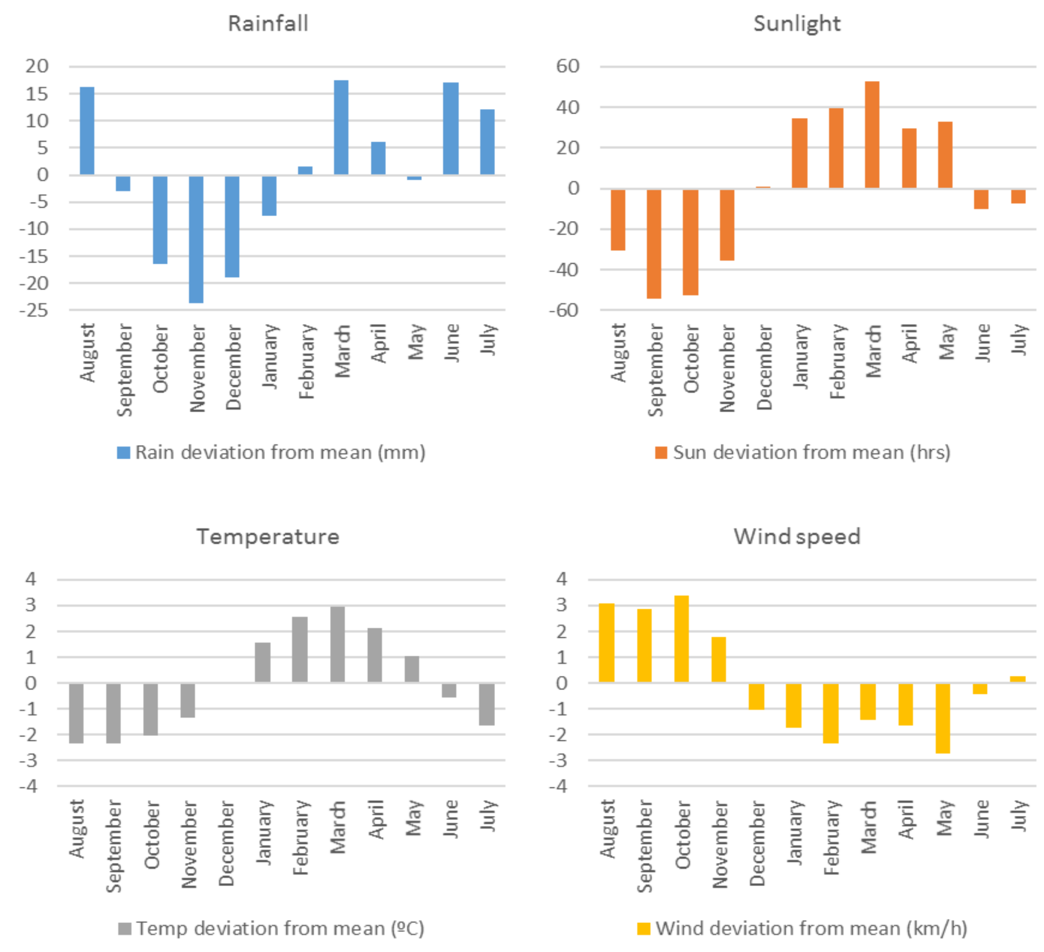


Figure 6 Monthly climate deviations from annual mean values

[7] http://sainthelenaisland.info/weather.htm

Wind, as determined by season, and aspect were also combined to create a 'wind exposure' node that influences the provision of timber. Land with a south-east aspect is more exposed to the prevailing wind on St Helena, so may be less suitable for timber production.

Soil quality, which in turn contributes to primary productivity, was determined from an interaction of soil carbon and soil pH, both of these were classified as either good, moderate or bad. Based on documentation for the relevant layers of the Habitat Map of St Helena (Pike et al., 2018), available via WebGIS[8], 'good' soil carbon levels were defined as between 5 and 10%, 'bad' was below 2.5% and 'moderate' was between 2.5 and 5% and above 10%. Soil pH between 5.5 and 6.5 is considered 'good', below 5 and greater than 10 was 'bad', with all other values 'moderate'. The combination of soil carbon and pH was based on the criteria used for the soil quality layer in the WebGIS, although soil conductivity was not included in the network. A full description of the data available in the WebGIS and how it was produced can be found in Pike et al. (2018).

A simplified representation of the final network showing linkages from forestry as a land cover type is presented in Figure 7. The relationship of different groups of nodes to the ecosystem services cascade is also illustrated. Land use or land cover and biophysical properties are the natural capital assets. These interact through ecosystem processes to produce ecosystem services. The ecosystem services then interact with a number of constraints to produce a number of benefits to people. The full network model is reproduced in Annex 1. The full network has a number of additional nodes not included in Figure 7. These may help simplify some interactions to reduce the size of subsequent CPTs (e.g. only altitudes above 690m are relevant for mist). Primary productivity is reproduced for each main land cover type, as scales of output are different, i.e. high productivity woodland sequesters and stores more carbon that high productivity pasture. There are other optional nodes such increasing agricultural inputs that may be of interest to users for some potential scenarios.

[8] https://data.saeri.org/saeri_webgis/lizmap/www/index.php/view/map/?repository=01sh&project=saint_helena_web

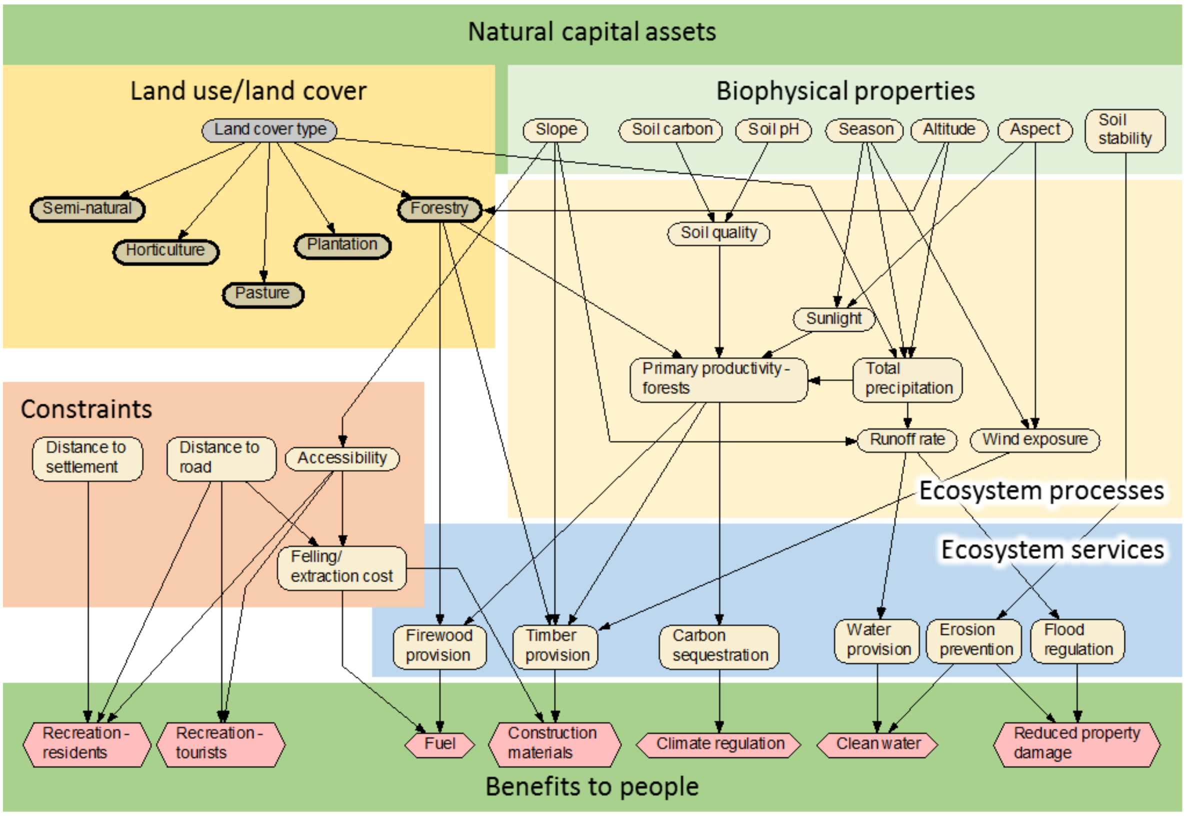


Figure 7 Simplified network for forest habitats

3.2. Data sources

The network, as described in the preceding section, can be used to estimate ecosystem service outcomes for user-selected land cover types, i.e. a specific state of the land cover type node is selected. This approach would also require the user to identity a series of corresponding states for the biophysical characteristics nodes (e.g. slope, soil carbon, soil pH, altitude etc.). These would need to reflect feasible conditions that are found on St Helena, although for any given land cover there may be variety of combinations of characteristics. To avoid this problem of identifying feasible representative combinations of the states of these characteristics we use a spatially based set of inputs drawn from different layers in the St Helena WebGIS (Pike et al., 2018).

A pixel size of 100 x 100m (or 1 hectare) is used for the input maps used in the model. Given that the area of St Helena is 121 km^2, this implies approximately 12,100 pixels. In effect the spatial model is evaluating a BN for each of these pixels. The output nodes of final ecosystem services are also represented in spatial format. These results will be discussed in section 4.

The land cover type map, Figure 8, describes the main habitats found on St Helena. It is based on data from several of the habitat maps available on the WebGIS with a degree of simplification to keep the subsequent analysis manageable. A composite approach was used to identify categories such as native versus introduced, e.g. some native habitat patches may be planted rather than natural due to habitat restoration. Flax is considered as a separate category is it has some unique characteristics. Rural gardens are included as they may provide important resources for pollinators. The 'other' classification includes barren and desert areas and buildings, these areas are not associated with ecosystem processes within the model, although in reality may be important for water flow and erosion. Revegetation of the some of these areas could be evaluated using the proposed user interface (see section 6.3).

In order to distinguish between forest stands used for timber production and those harvested for firewood, data from the Agriculture and Natural Resources Division (ANRD) of the St Helena Government was used to identify types of forest stand within the public forest estate (Figure 9). These included a large are of dual purpose woodland (timber or firewood), to distinguish use within the network we assigned pixels above 500m to timber as per information from forestry staff. Figure 10 presents the maps of the biophysical characteristics that had spatially based inputs into the BN.

Figure 11 illustrates mapping of some the constraints on ecosystem services. These reflect the difficulty of accessing resources for uses such as timber, firewood or recreation. Although much of the existing forestry has been planted in accessible areas, future expansion scenarios may be sensitive to accessibility constraints. Current harvesting techniques may also have different access restrictions than when forest stands were originally planted.

We treat recreational potential differently for St Helena residents and tourists[9]. We assume that residents will be more likely to utilise sites closer to settlements, whilst tourists may be less constrained. Both residents and tourists are assumed to be more likely to utilise areas both close to roads and paths. The distance to path (and to a lesser extent the distance to road) map lacks some sensitivity as the distance bands used are smaller than the 100m pixel size used for the analysis. The distance bands use for settlements, road and paths are based on the judgement of the project team. Given the accessibility and high slopes of many areas, there may be far harder boundaries in some areas, e.g. the Diana's Peak ridge path (Figure 12), although 'accessibility' as defined by slope is included as an additional constraint.

[9] We use the term 'recreation' in a very broad sense that could capture a variety of cultural ecosystem service motivations.

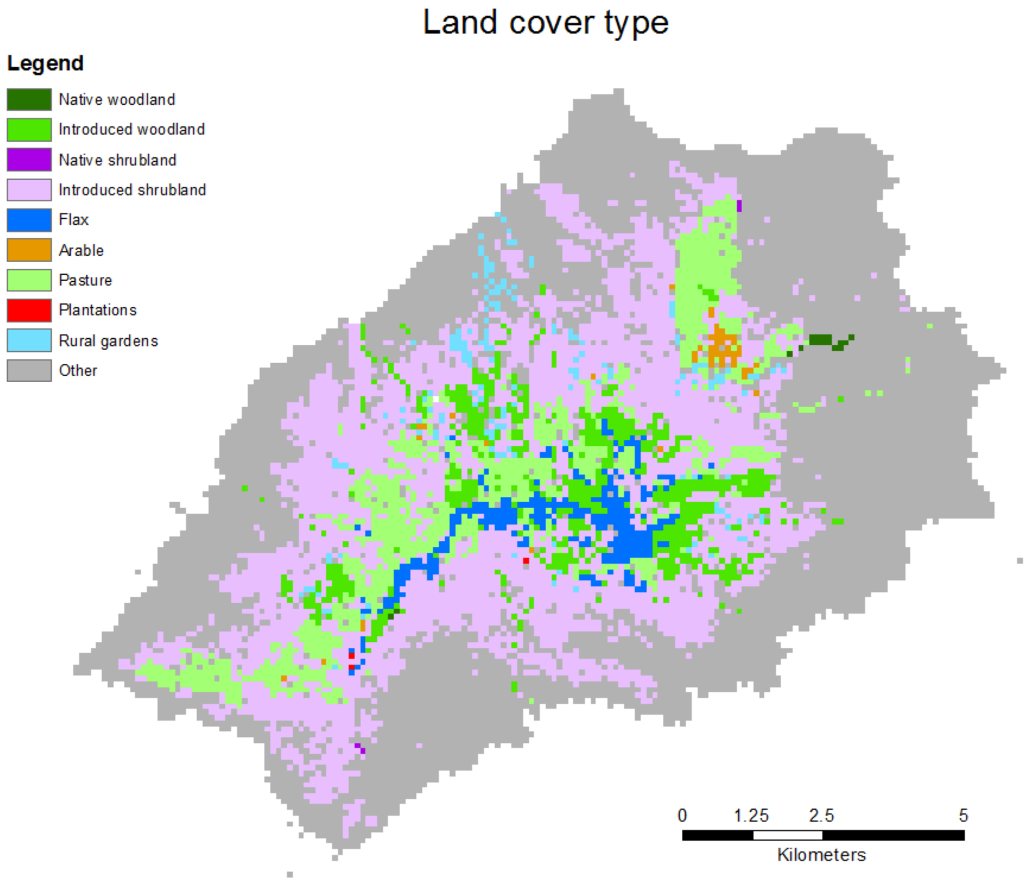


Figure 8 Land cover type input map

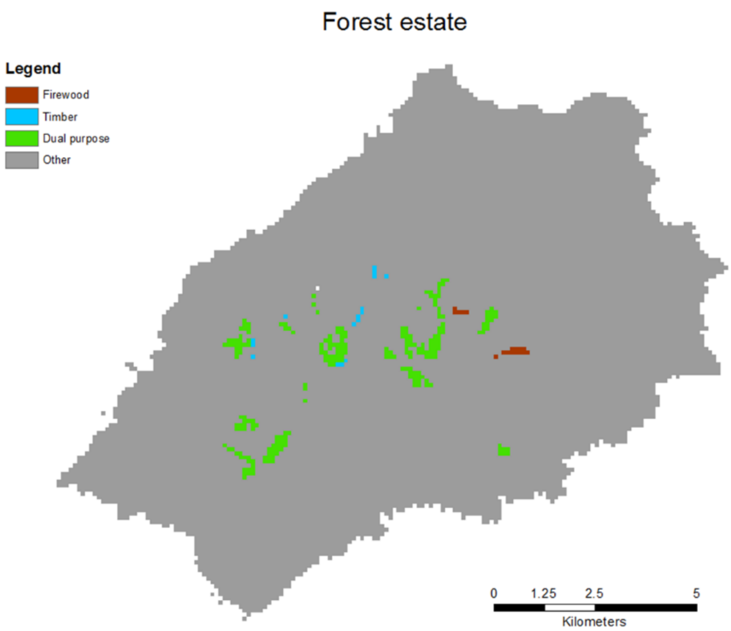


Figure 9 Forest use within the forest estate

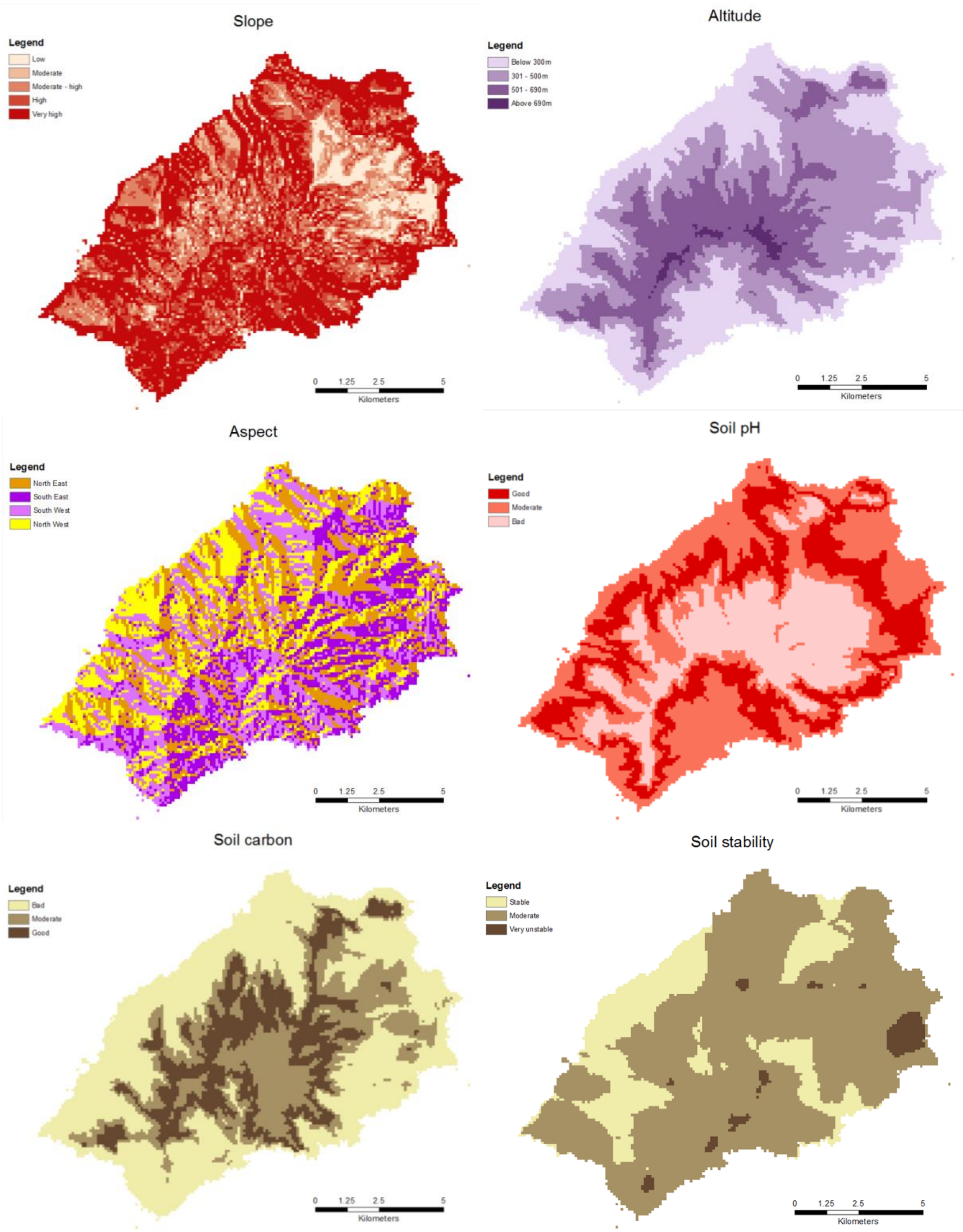


Figure 10 Biophysical characteristics input maps.

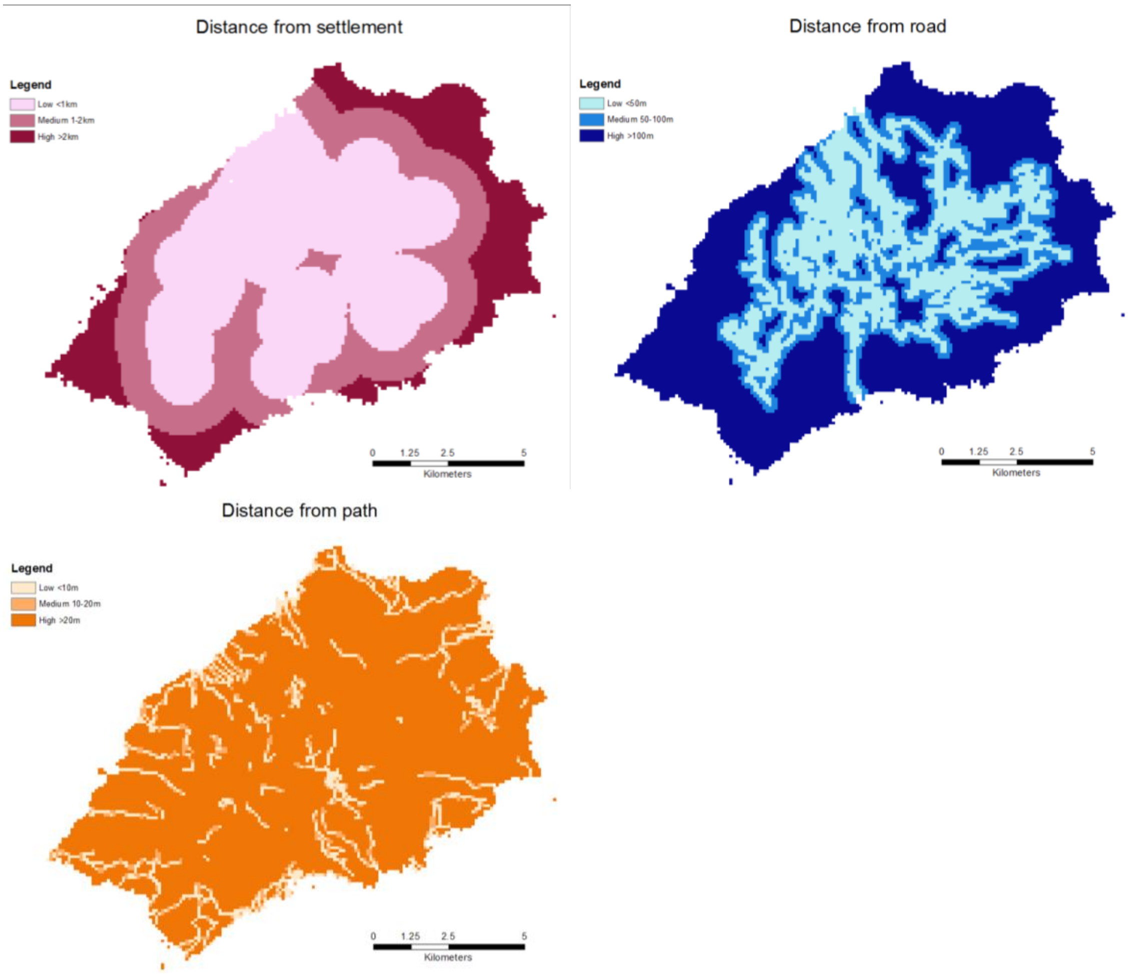


Figure 11 Constraints maps

Figure 12 Diana's Peak ridge path (source: McVittie)

3.3. Modelling approach

The development and analysis of the spatial BN is undertaken in the Netica package[10], this was used due to familiarity and a straightforward user interface. The spatial element of the BN analysis was undertaken in R using the 'bnspatial' package (CEH and NERC, 2019)[11]. However, the Netica file format cannot be directly read into R. Consequently, a further intermediate stage was required, with the Netica files imported into another Bayesian networking package, GeNIe[12], then saved into a format readable by R. Future application of the approach, or amendments to the current model, could be achieved using a BN package readable by R (e.g. GeNIe, Hugin) or through suitable R packages (e.g. bnlearn)

The 'bnspatail' package reads the input maps (as tiff files) into R, applies these to the Bayesain network, then writes the output maps to tiff files. A number of output maps can be produced for each output node. These include maps showing the most probable outcome state (e.g. high, medium, low) for each pixel, the probability associated with each output state, and the entropy or uncertainty associated with the predicted outputs.

The spatial approach does require considerable processing time. The pixel resolution of the input and output maps is 100 x 100m (i.e. 1 hectare). Given the area of St Helena, that implies approximately 12,100 pixels, each of which is run through the BN model. It would be possible to produce mapped outputs for a wider range of the BN nodes, for example, key intermediate processes, however this would be at the cost of additional processing time.

10 Produced by the Norsys Software Corp https://www.norsys.com/netica.html.
11 https://cran.r-project.org/web/packages/bnspatial/index.html
12 https://www.bayesfusion.com/

4. Results

In this section we present the results of the 'basic' BN model (illustrated in Annex 1) which considers the current land use on St Helena. The results maps produced from the 'bnspatial' package in R are in raster format (tiff files), these were processed in ArcGIS. The results are presented in terms of the different ecosystem services categories.

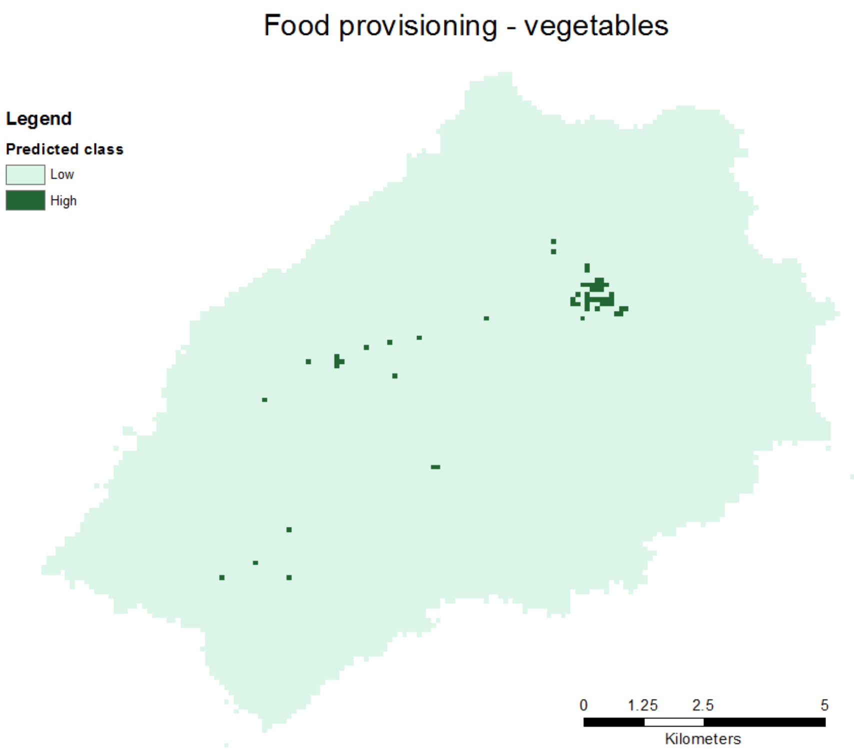
4.1. Provisioning services

The provisioning services included in the BN are food (vegetables and meat), timber and firewood, and clean water. We do not assess the actual production of these services, instead given the natural capital conditions, we assess the potential for each pixel of relevant land use or habitat to produce these services. For example, we do not consider the actual harvesting of timber or firewood, the types of vegetable or crops grown, the stocking rate or types of livestock. Indeed the provisioning of livestock is strictly speaking the provisioning of pasture, so reflect the biomass available to feed grazing livestock. The results for coffee production (related to the land use 'plantation') are not presented as this currently relates to a very small number of pixels.

Figure 13 presents the potential provisioning of vegetables. Both the predicted class (high, medium, low) and the probability that the class is 'high' are presented. This illustrates a possible issue with interpretation. The predicted class simply identifies the pixels that are currently used for horticulture. The probability of 'high' offers more sensitivity as within those pixels used for horticulture it potentially identifies those pixels that are likely to be more productive given the condition of the associated natural capital. The issue with interpretation is a question of how we deal with the different probability values. For example, what are the particular thresholds, and what do these imply for management or policy?

The probability values in Figure 13 range from 0 to 0.6, the lowest class (0 – 0.189) reflects the state 'low' where no horticulture occurs. The remaining classes reflect different output potential within the area used for horticulture. A possible interpretation is that those pixels with lower probability values are subject to greater constraints on productivity such as slope, aspect, and soil quality. This would suggest areas that might benefit from higher inputs or advice on improving productivity to overcome those constraints.

Figure 14 illustrates the outcomes for the provisioning of meat, or the provisioning potential of pasture. The predicted class map is less informative and corresponds to areas of existing pasture. The probability of 'high' map shows more detail of the pixel where productivity is predicted to be higher reflect the nature of the underlying natural capital.



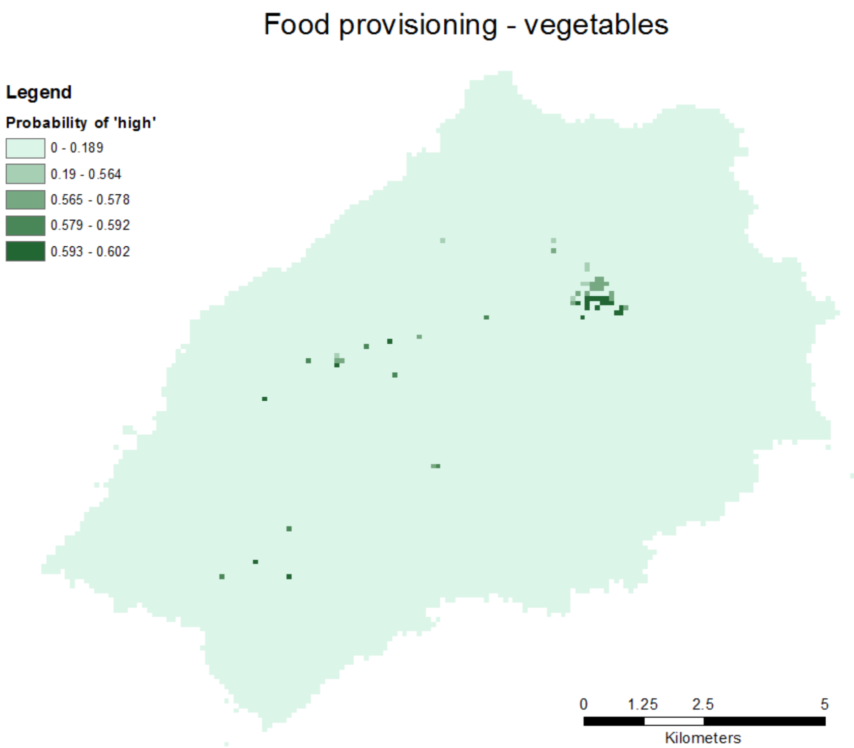
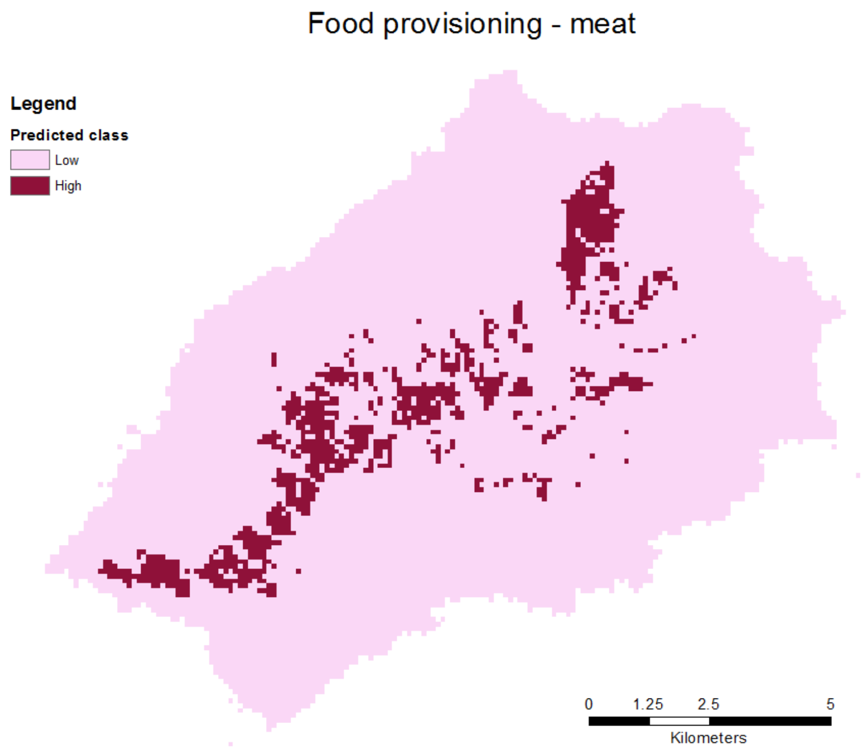


Figure 13 Provisioning of vegetables, predicted class and probability of 'high'



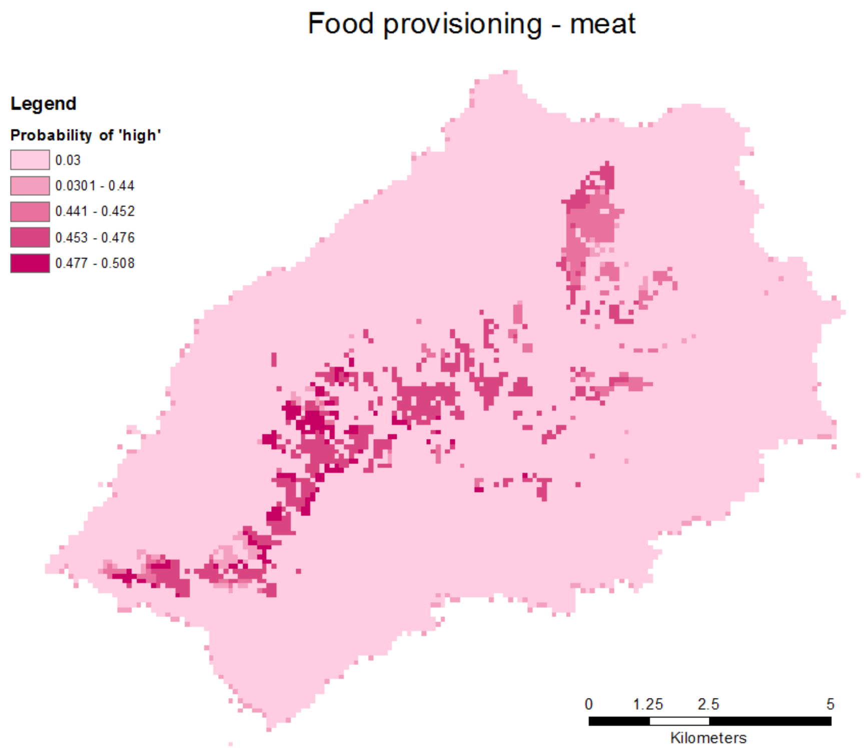
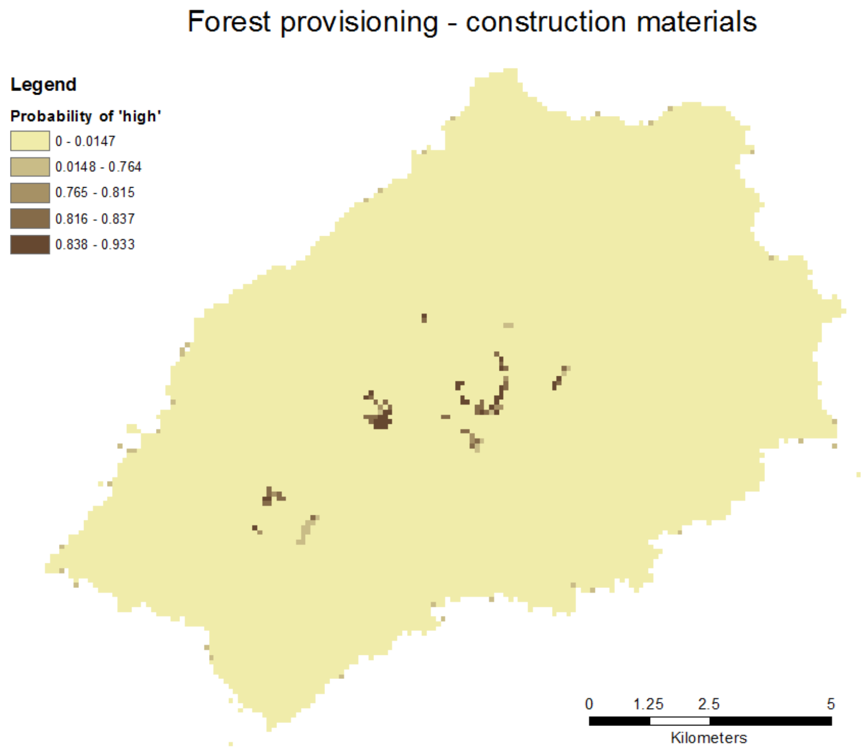


Figure 14 Provisioning of meat, predicted class and probability of 'high'

The provisioning of timber and firewood are illustrated in Figure 15, these maps show only the probability that the output class is 'high'. As with food provisioning the variation in these probabilities reflects the underlying natural capital assets and in this case further constraints added to the BN, specifically forest harvesting is more difficult on higher slopes and further away from roads. Note also the relatively low probabilities for 'high' in respect of firewood (<0.347), this reflects the model outcome that also allows pixels to be classified as either 'low' or 'medium'. Although no pixels were classified as 'high' it is arguably sensible to present the probability of 'high' in cases where this is considered the 'best' outcome. Essentially, given the accessibility constraints on firewood provision that we have added to the model, the current areas used for this purpose do not perform at the highest level the model would allow.



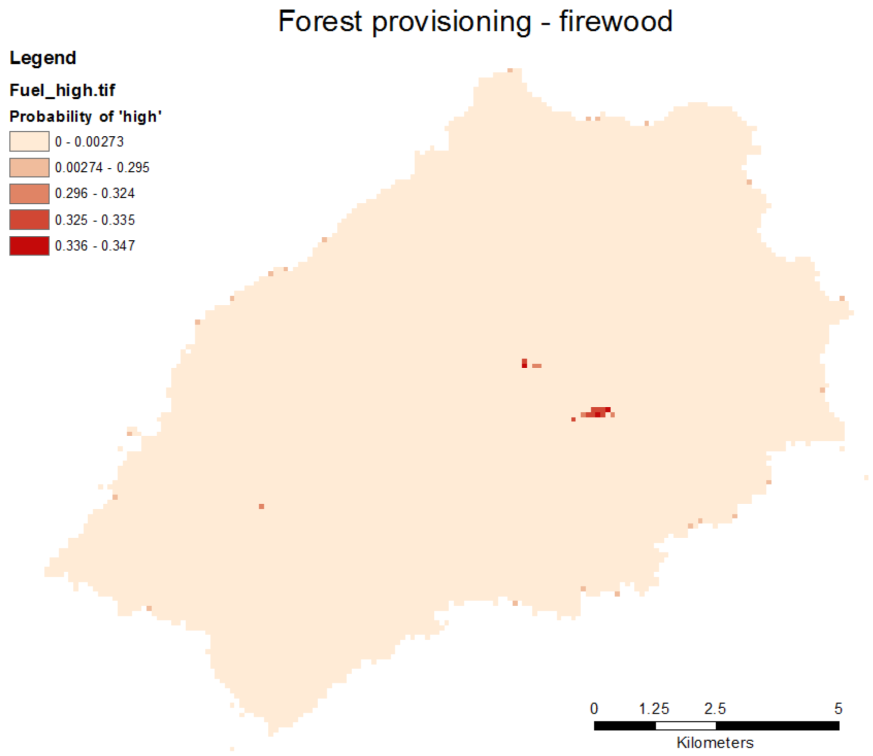
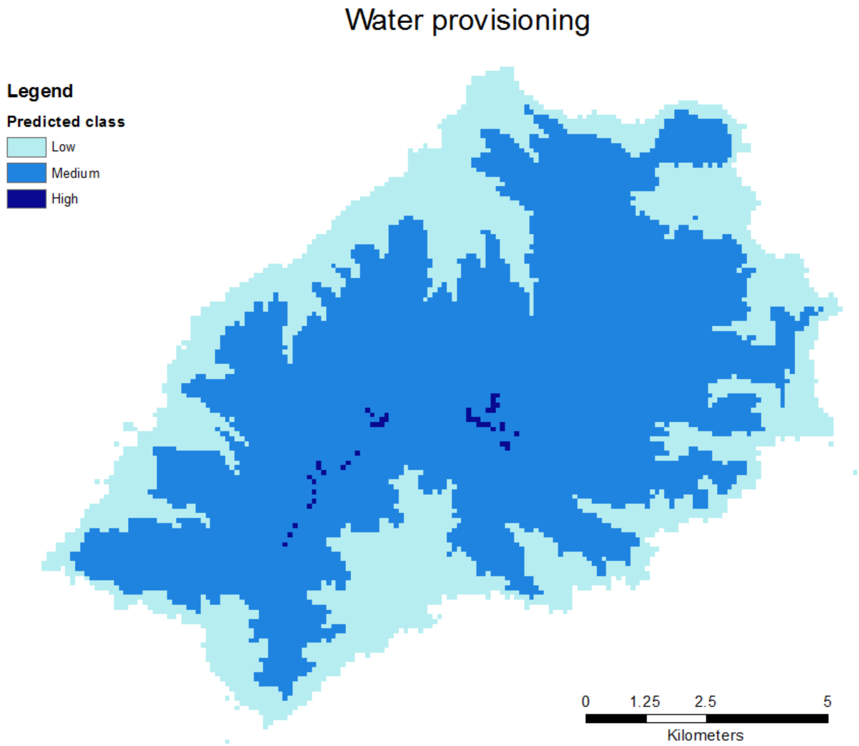


Figure 15 Provisioning of timber and firewood

Figure 16 presents the predicted class and probability of 'high' for water provisioning. The small areas of 'high' related to both the altitude and habitat types most closely associated with mist capture. The variation in probabilities of 'high' (mostly in areas classed as 'medium') will reflect how the interactions of slope and habitat type influence runoff rate, i.e. slowing down flows to retain water in the system. There is also a quality aspect within water provisioning, this is driven by the degree of erosion which relates to soil stability and runoff rates.



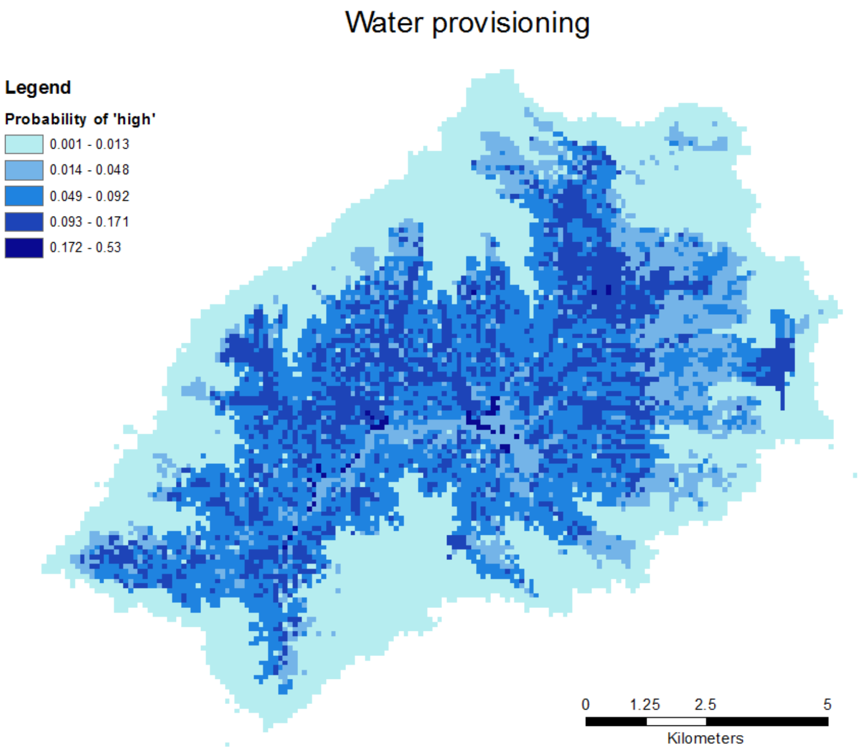


Figure 16 Water provisioning

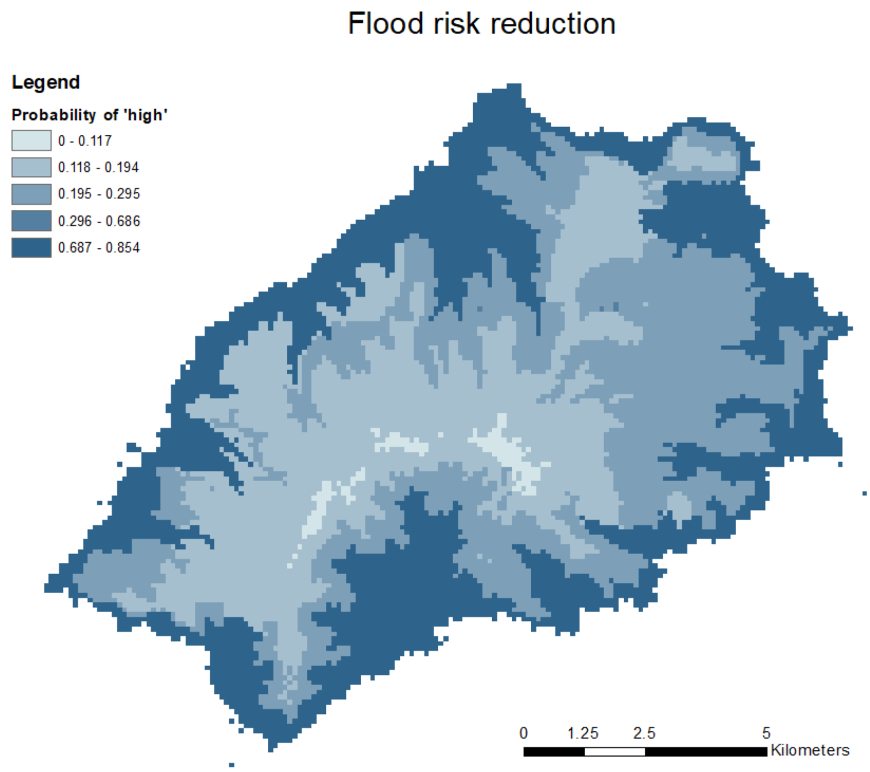
We note a couple of interesting observations that can be made from Figure 16. There is a relatively low probability of high water provisioning in the areas associated with flax (see Figure 8), this reflects the high runoff rates associated with flax. This is due to the low evaporation from, and flow in, the peaty soils below flax plants, that soil remains saturated; consequently, there is little infiltration. St Helena airport is also predicted to have relatively high water provisioning; this reflects the relatively large expanse of flat land with an associated low runoff rate.

4.2. Regulating services

The BN evaluated a number of regulating services including flood risk reduction[13], pollination and carbon sequestration. Figure 17 presents the probability of 'high' for flood risk reduction, represented in the model as reduced damage to property. The most obvious result in the model is the high probability assigned to the least vegetated coastal areas. This reflects the low level of precipitation, both from rainfall and mist, associated with these areas due to their relatively lower altitude. The lack of vegetation would result in a heightened risk of flooding and associated erosion and this is reflected in the 'Water runoff rate' node of the BN. The lightest area (i.e. higher flood risk) is related to the area of flax. Figure 17 also shows the probability of the node state being 'medium'. This suggests there is more variation across pixels than shown in the probability of 'high' map. It perhaps reflects the relatively low performance across the island with respect to this service.

A limitation of the model is that reduced flood risk or property damage is related to only the natural capital conditions in each pixel. It does not reflect the number of 'receptors' or beneficiaries of the service. Further user interpretation is needed to determine the extent to which the service is actually received. There would also be cumulative impacts, for example, high runoff from flax might be mitigated by downstream habitats.

[13] This incorporates an element of erosion reduction.



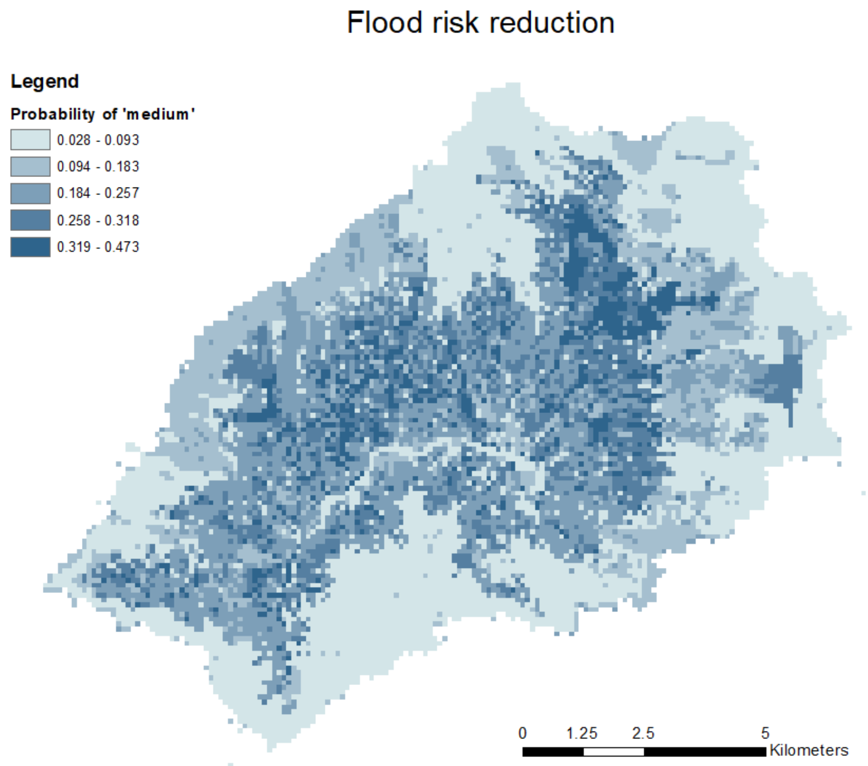


Figure 17 Flood risk reduction – reducing damage to property

Potential pollination services are illustrated in Figure 18. Pollination was linked to a final benefit of honey production, although this is a provisioning service the model is considering potential rather than actual production, but the regulating service does remain regardless of actual honey production. The drivers of pollination were within pixel primary biodiversity, given higher probability for native vegetation, and landscape biodiversity which reflects the variation in surrounding habitats and associated nectar sources.

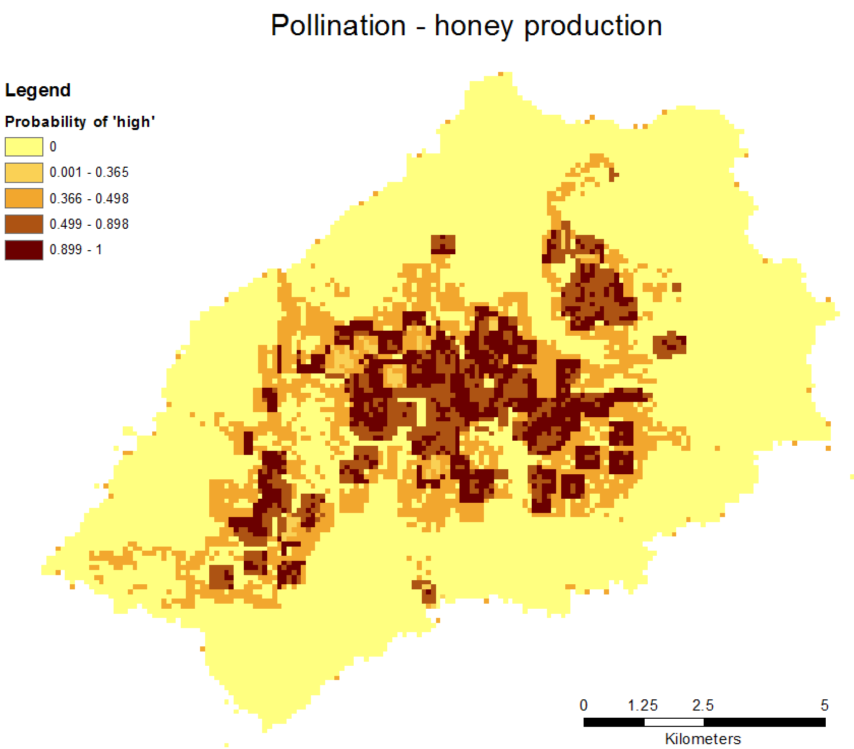


Figure 18 Pollination services

Figure 19 presents the probability of ‘high’ carbon sequestration. This relates to both semi-natural and managed forest areas, and reflects areas that could be readily used to measure carbon for off-setting purposes. Arguably, carbon sequestration in this respect is more relevant for land use change scenarios. These are explored in the following section.

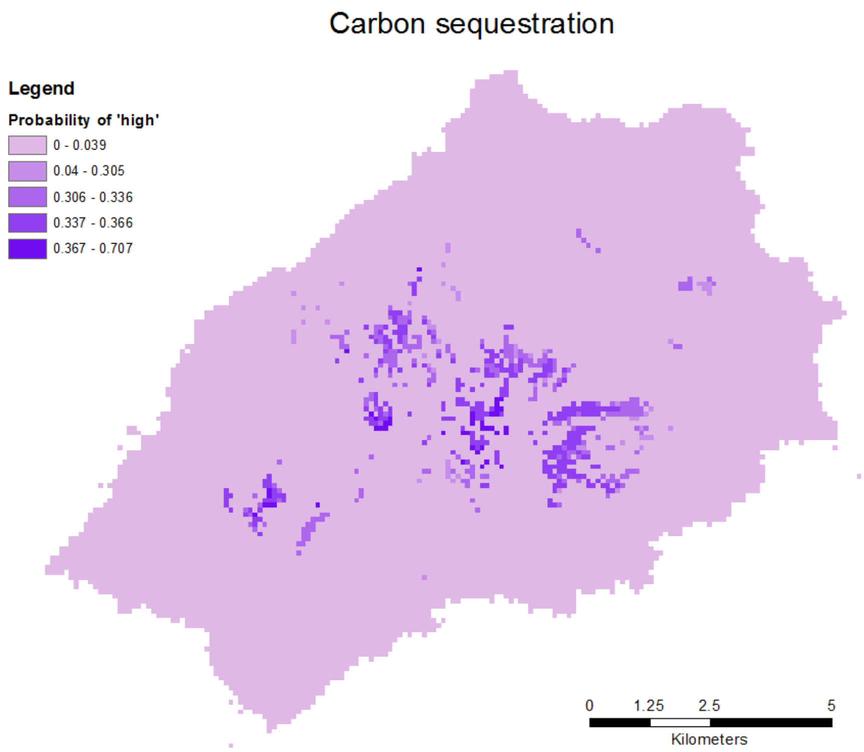


Figure 19 Carbon sequestration

4.3. Cultural services

In the BN, cultural services are represented by the potential recreational opportunities offered by different habitats[14]. No specific type of recreation is defined and could include walking in woodland or gardening (for local residents). We also include constraints based on accessibility and proximity to settlements for local residents and proximity to roads and paths for both residents and tourists. The aim is to identify the potential recreational opportunity provided by each pixel rather than actual recreational use. However, data from Bormpoudakis and Fish (2019) can be used to compare predicted recreational opportunity with actual recreational use.

Recreational potential for residents is illustrated in Figure 20. The BN output has been overlaid with spatial results from a survey of local residents by Bormpoudakis and Fish (2019), specifically points identified by locals as important for leisure. The comparison indicates that there is a reasonable agreement within habitats in centre of St Helena. The key omissions from the BN are coastal areas and unvegetated area, as these habitats were not included in the model. This could be refined by altering the associated CPT to allow recreation where there is a path present (see Figure 11). The BN also does not estimate recreational potential for urban areas such as Jamestown.

Similar results can be seen for recreational potential for tourists in Figure 21. Bormpoudakis and Fish (2019) undertook an analysis of geotagged posts on the photo sharing site Flickr to identify the sites of tourist interest. Coastal and marine sites are a clear omission as with for locals. There also appears to be a high number of observations for sites of cultural and historic heritage, for example Longwood House, Napoleon’s Tomb and Jamestown.

[14] Under the CICES system these would be ‘experiential interactions’ that could cover a variety of uses including formal and informal recreation.

Regardless of the results of the comparison, a key motivation of including recreational opportunity in the BN model was to allow comparisons of different land uses. In particular, can the potential benefits of recreation for health and well-being inform future land use change scenarios?

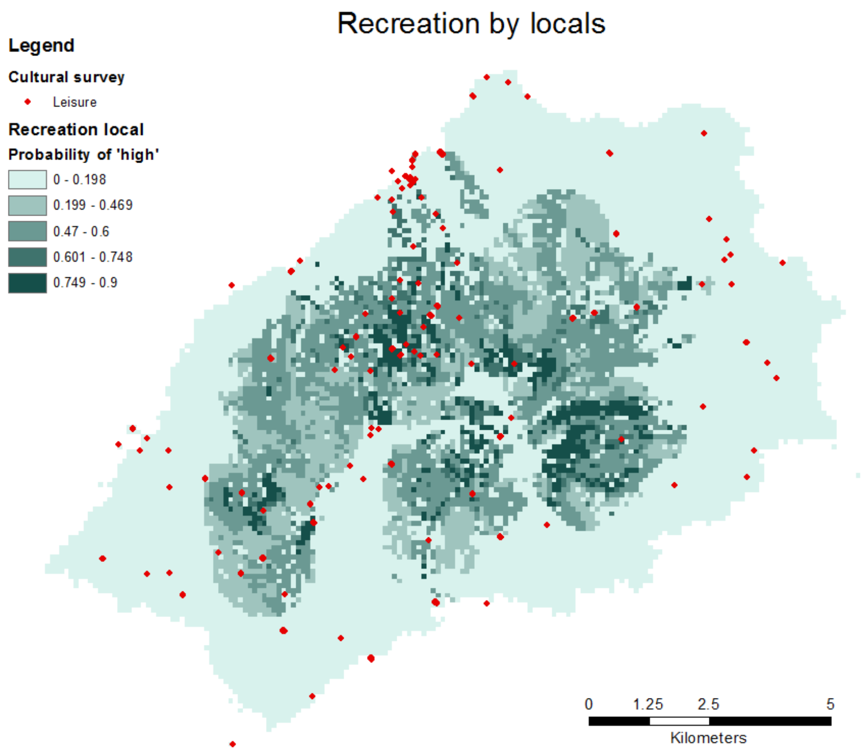


Figure 20 Recreational potential for local residents

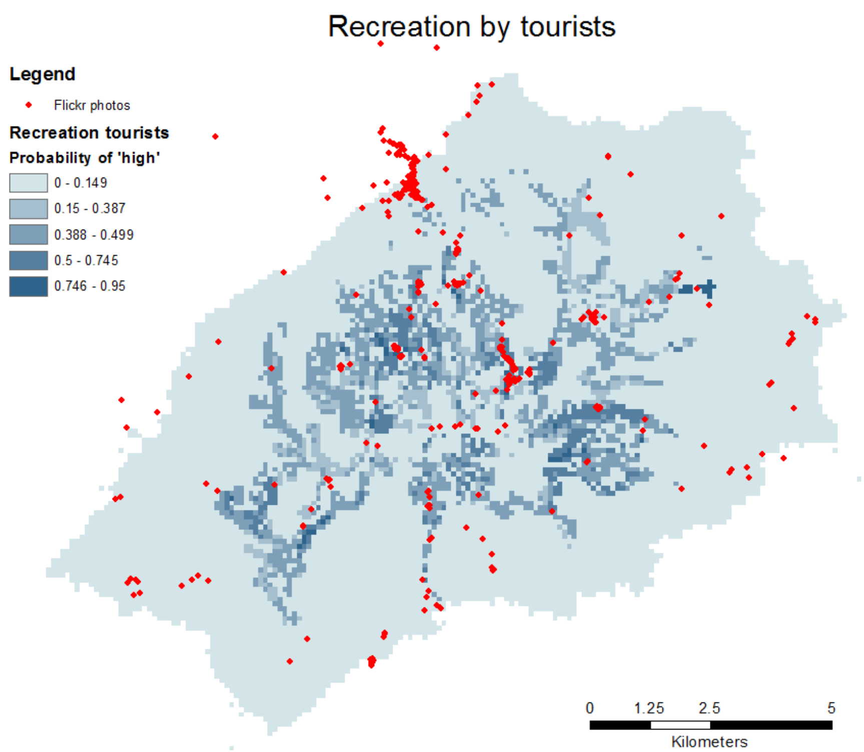


Figure 21 Recreational potential for tourists

5. Scenarios

Stakeholder workshops were held on St Helena in October 2018 to identify future scenarios for St Helena (Pelembe and Smith, 2018). The workshop developed a series of narratives of different development paths out to 2030. These differed in respect of the degree on engagement St Helena may have with the outside world and the sustainability or greenness of the economy. The associated narratives developed by stakeholders inare presented in Table 2.

Each of these scenarios will have a variety of impacts on St Helena's natural capital, whether that is to increase or reduce reliance on some parts of it, to negatively impact upon it or to enhance it. However, the BN model primarily assess the impacts of land cover type on ecosystem services subject to the underpinning natural capital conditions. Based on the scenario descriptions a number of land use changes were selected for evaluation.

Expanding horticultural output – mapping potential new horticultural field sites based on current land cover being pasture (the most suitable for conversion), low distance to roads and low slope.

Expansion of honey production – this is already be incorporated to an extent in the BN model, as the honey output node reflects pollination services rather than actual production. The expansion of honey production is evaluated by including constraints on honey bee hive locations such as accessibility in terms of slope and distance from roads.

Expansion of coffee production – this is evaluated by considering potential pollination services and altitude together with constraints based on accessibility in terms of slope and distance from roads.

Expansion of forestry – Forestry expansion could serve to increase either timber of firewood production. The BN evaluates the potential of existing non-native forest and non-native shrubland sites based on accessibility in terms of slope and distance from roads. The associated ecosystem services of water provisioning, flood regulation, carbon sequestration and recreation are also included in the model. Native habitats, horticulture, pasture, plantations, rural gardens and 'other' are excluded from forestry expansion[15].

Expand renewable energy – wind and solar potential can presumably be met on barren land which is not covered by the BBN. Hydropower, would be difficult to model as hydrology is not covered (flow volumes etc.). The scenario instead considers expansion of biomass production. We assess this in a similar way to the expansion of forestry with the additional potential for land use change from pasture reflecting the potential for a wider range of biomass crops beyond firewood. Constraints in terms of slope and distance to roads are included.

Removal of flax – removal of this invasive species could either be for forestry or restoration of native species. The suitability for forestry production would be related to slope and distance to road as these would impact on the ease of future harvesting. For both forestry and native species restoration the model can be used to evaluate a range of ecosystem services including timber or firewood production (under forestry), water provisioning, flood regulation, carbon sequestration, and recreation.

Expansion of settlements – opportunity mapping of areas most appropriate for development, i.e. close to roads and with low/moderate slope. The model allows for development on all non-native habitats with the exception of horticulture, plantations and rural gardens.

[15] 'Other' includes barren land and buildings, the latter would be excluded from forest expansion, the former may not be suitable given altitude and low precipitation.

Table 2 Summary of St Helena scenario narratives

Scenario	Narrative
Global green island	• St. Helena is accessible by sea and air and tourist ships visiting have increased. • Increased numbers of discerning visitors who stay in eco-lodges, and undertake more voluntourism activities. • High speed, affordable internet, connectivity enabling improved education, health services, increased knowledge export. • Green pedestrianised urban areas and increased eco-transportation. • Increased renewable energy sources. • Increased exports of niche products • Improved environmental management. • Increased international events. • Appropriate governances arrangements to facilitate sustainable economic living. • Producing significantly more food supplies through agriculture and fishing. • Lifestyle related illnesses reduced through healthier lifestyles.
Isolated green island	• St. Helena is only accessible by sea, with a cargo ship arriving on a six weekly basis. • Meeting much more of food demand through local production. • Re-using and recycling much more of our production to meet our needs. • Environment management has increased through improved invasive species management. • More reliant on traditional life styles (water, energy, building etc) and methods of living. • Fish stocks are replenished through traditional fishing methods. • Using less advance technology and people are involved more in community projects. • Population is managed.
Aggressive global island	• St. Helena will have aggressive economic growth and be part of the global village. Increased flights, facilitating increased tourism. • Increased development with more hotels, and tourism. • Increased resident population enjoying an improved quality of life including an availability of housing. • Traffic and the generation of waste have increased, this is being managed effectively. • Fibre optic cable has enabled access to more advanced technology. • 100% renewable energy and utility prices are low and affordable. • Agricultural production has increased and the export of honey, coffee and fish has been facilitated. • All locals have access to honey.
Aggressive isolated island	• St. Helena though isolated, has aggressive economic growth. • Fewer flights but will attract high value, low volume, tourists. • Niche tourist markets supported by innovative planning and construction and eco-friendly design using locally available materials. • The main industry is the digital sector enabled by satellite ground stations and fibre optic cable. • People are working from home and selling services via the internet. • E-banking is used widely. • Sustainable agriculture and fisheries and local culture is preserved. • The island has become a living laboratory for research and there is less influence on our marine environment.

5.1. Expansion of food production

The potential sites for expanding horticulture are illustrated in Figure 22. These are on areas currently classed as pasture with relatively low slopes and close to road to allow access. In comparison to Figure 13 there appears to be significant opportunity for expansion of the horticultural area. Notably, there is a large area of high potential to the north of Longwood close to the existing concentration of horticultural land. The BN does not consider the opportunity cost of the land use change or the institutional constraints based on ownership or tenure, or National Conservation Areas. Other constraints such as water supply are also not considered. Connection the existing water supply network including costs of supply, or potential for impoundment would need to be evaluated.

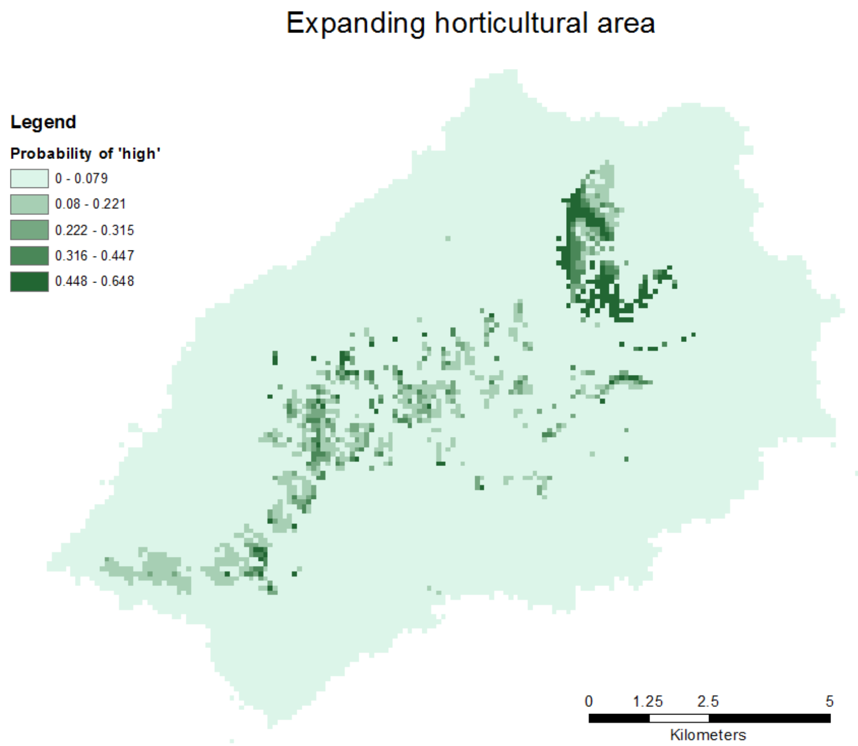


Figure 22 Expanding horticultural production

Figure 23 illustrates the areas that could be suitable for expanded coffee production. This reflects altitudes over 500m, pollination and the state of inputs into primary productivity: precipitation, sunlight and soil quality. The area is constrained by slope and distance to roads, with more accessible areas being favoured. The BN constrains expansion based on existing habitat type with only introduced forest, introduced shrubland, flax and pasture being possible areas.

The potential areas for expansion of honey production as presented in Figure 24. In comparison with pollination services potential in Figure 18, the scenario appears to show an increase in the area suitable for expanded honey production. This is an interesting outcome as the scenario takes the pollination services as the primary driver and combines this with accessibility, so areas without high pollination potential will always have lower honey production potential. However, the key result is that the extent of areas with the highest probability of honey production being 'high' has been reduced due to the inclusion of accessibility. Consequently, although the scenario indicates a wider area could be used for honey production, the most suitable sites are narrower, indicating where production would be better targeted.

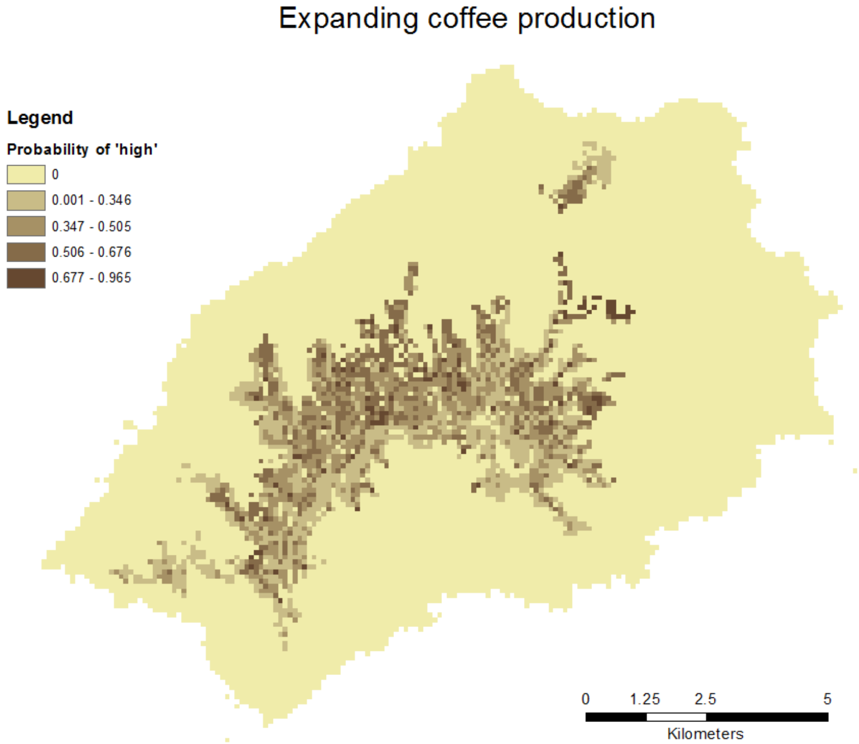


Figure 23 Expanding coffee production

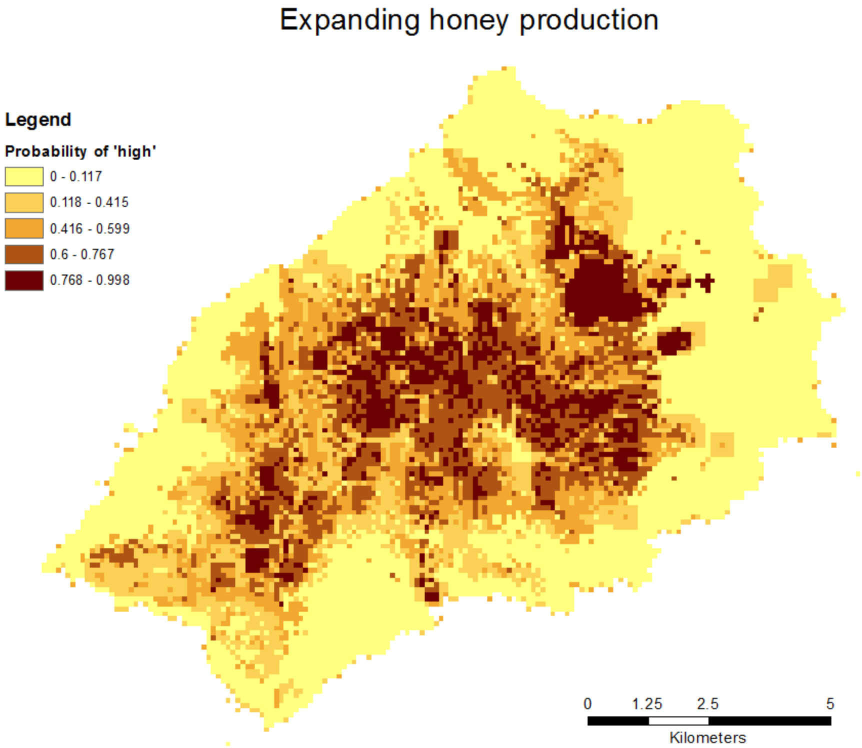


Figure 24 Expanding honey production

5.2. Expansion of timber production

Land has recently been removed from the forestry estate. This scenario investigates where opportunities exist to expand production, although does not consider constraints such as protected areas. Figure 25 illustrates the outcome of the timber expansion scenario. Expansion was constrained to areas of introduced woodland, shrubland and flax that are also accessible in terms of proximity to roads and slope. Despite the constraints, the scenario indicates that there is considerable scope for timber expansion across St Helena.

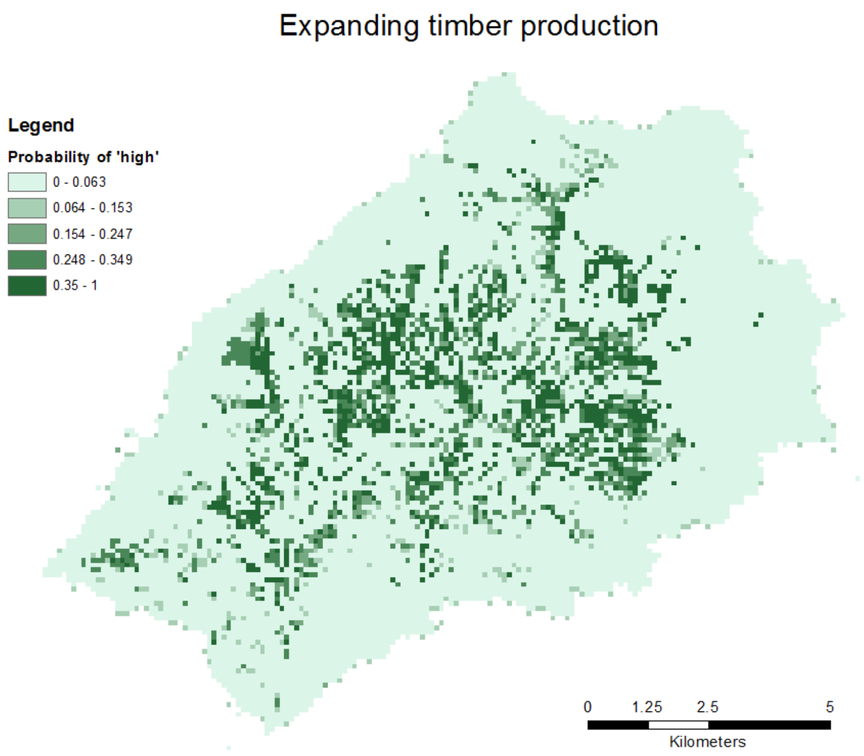


Figure 25 Expansion of timber production

Figure 26 illustrates the water provisioning potential from expanding timber production. This arises from maintaining woodland cover in existing forest areas and potentially expanding woodland to existing introduced shrubland and flax habitats. Two maps are included, one showing the probability that water provisioning will be 'high' the other that the level will be 'medium'. The outcome is interesting in that high levels of water provisioning are largely restricted to land above the 690m contour where there is a greater potential for mist capture. This reflects a slightly different parameterisation of the relevant CPT when compared to the general water provisioning map shown in Figure 16. This is an interesting illustration of how BN results need to be interpreted in relative terms. In that sense the two maps or not readily comparable. Note also that the probability levels for 'high' in Figure 16 are relatively low. For a more general assessment of where expanded timber production could improve water provisioning the probability of 'medium' is appropriate, although this largely reflects processes such as moderating runoff.

Moderating runoff is also a key process in flood risk reduction. The potential for expanded timber production to deliver this service is illustrated in Figure 27. Here both vegetation type and slope are important parameters, although the scenario would not generally favour woodland for timber on higher slopes, so the potential for the service will be restricted.

Figure 28 illustrates the potential for carbon sequestration through expansion of timber production. This largely reflects the suitability of each pixel for timber production, i.e. through its accessibility. Accessibility to roads and paths and lower slopes is also the driver of suitability for recreation as illustrated in Figure 29.

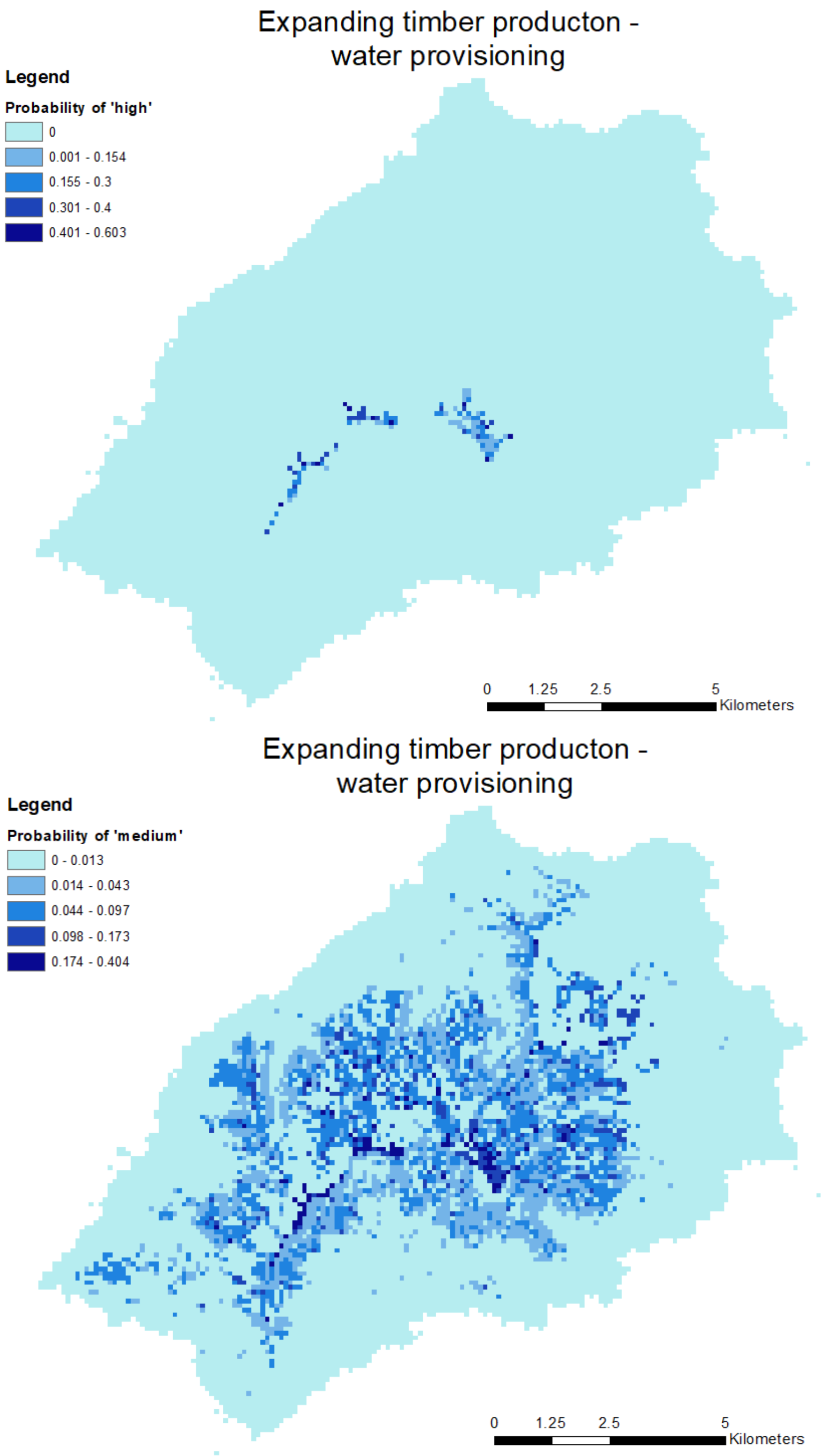


Figure 26 Expanding timber production – water provisioning, probability of 'high' and 'medium'

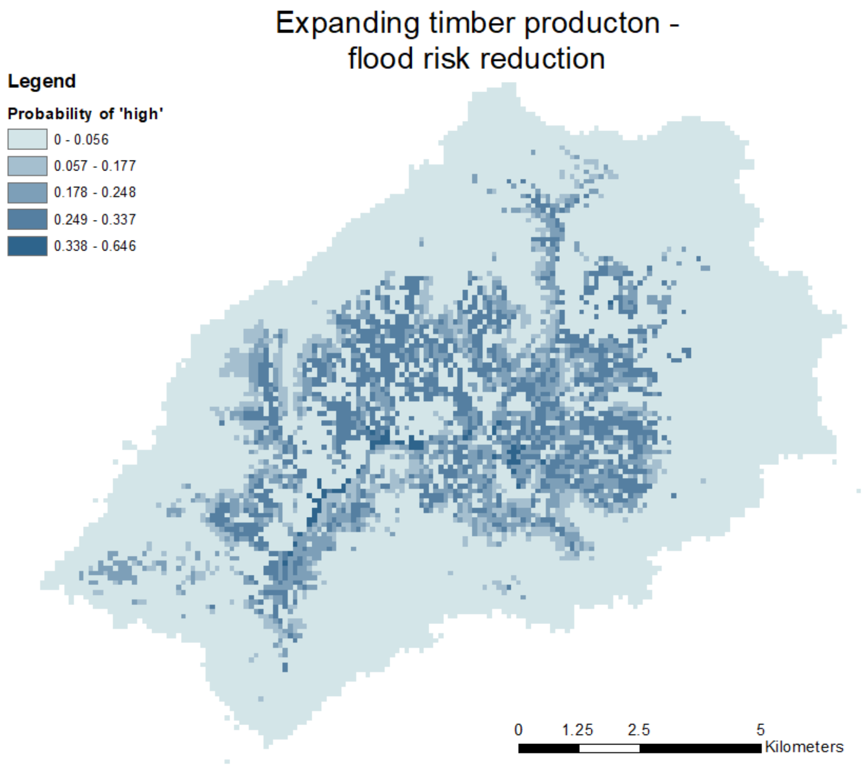


Figure 27 Expanding timber production – flood regulation

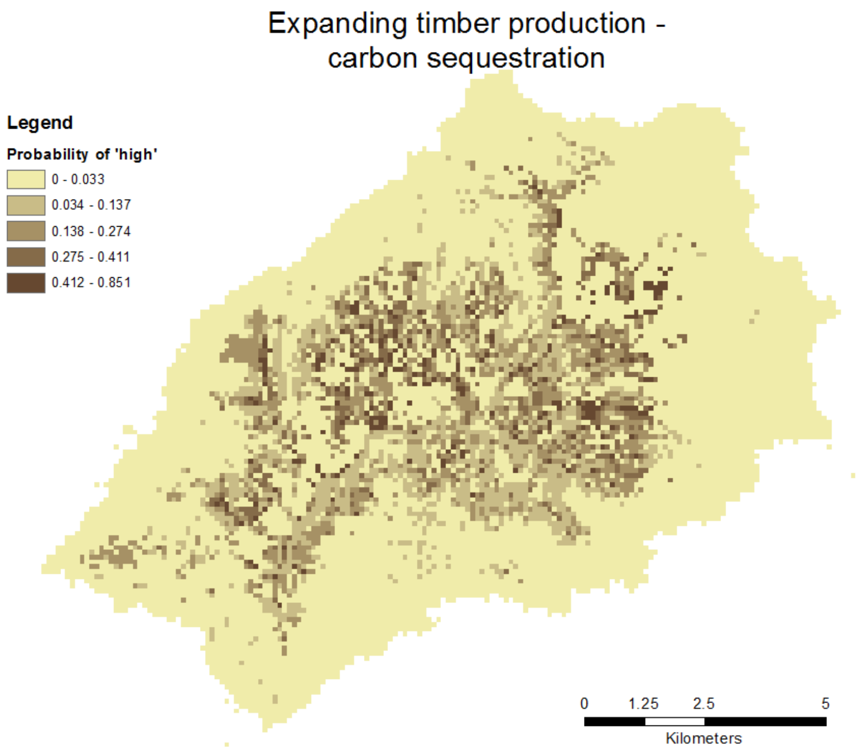
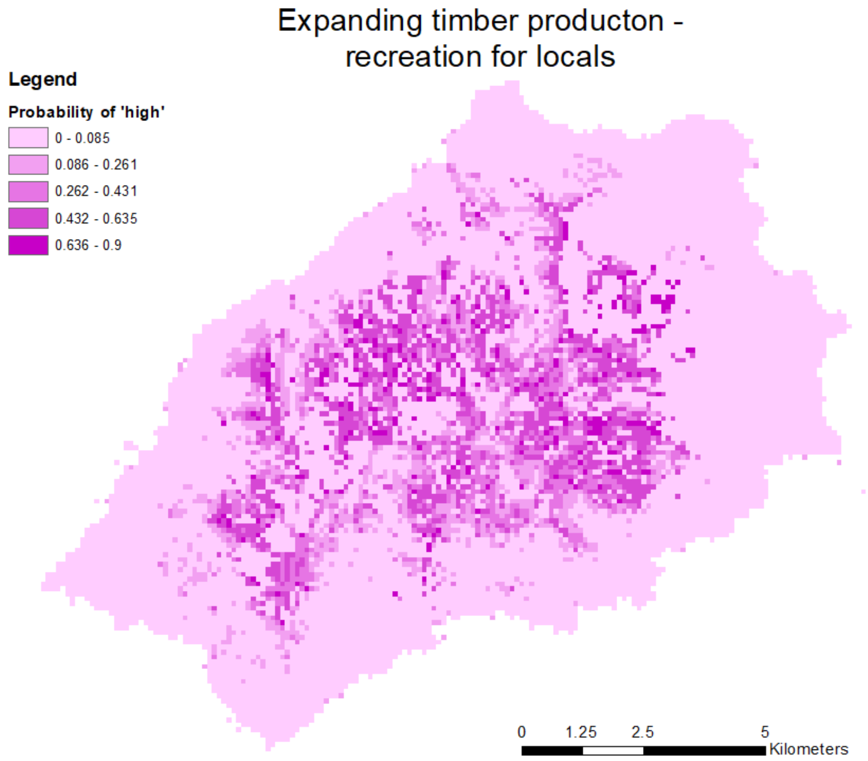


Figure 28 Expanding timber production – carbon sequestration



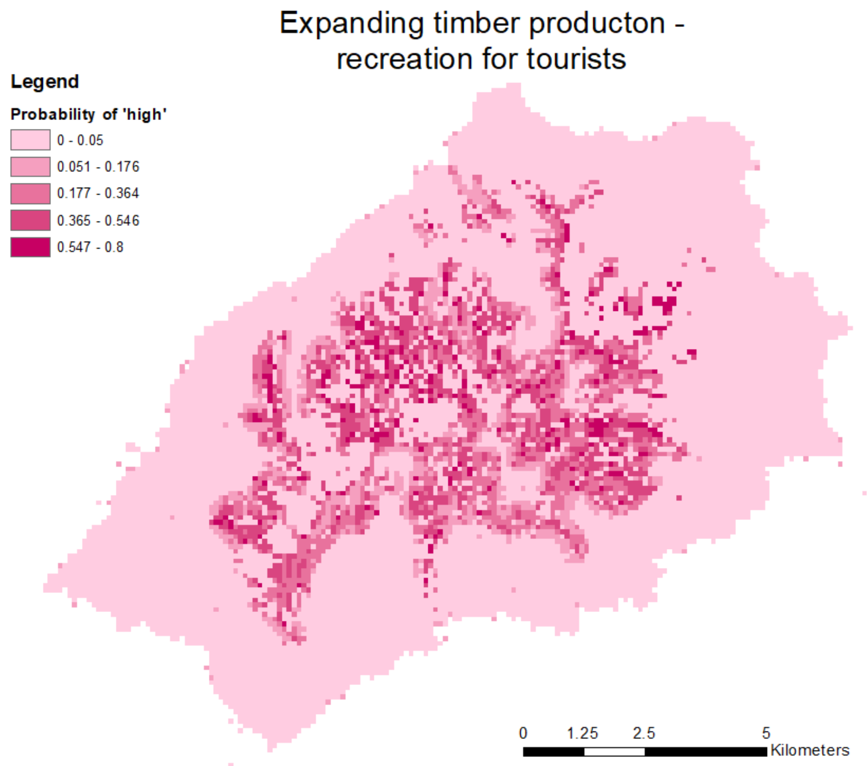


Figure 29 Expanding timber production – recreation for locals and tourists

5.3. Expansion of biofuels

The areas for biofuel production illustrated in Figure 30, indicates considerable potential for expansion. This largely reflects the potential to convert some pasture to biofuel growth, the intention being that this relates to crops such as Miscanthus or short-rotation woodland as well as firewood production on non-pasture areas.

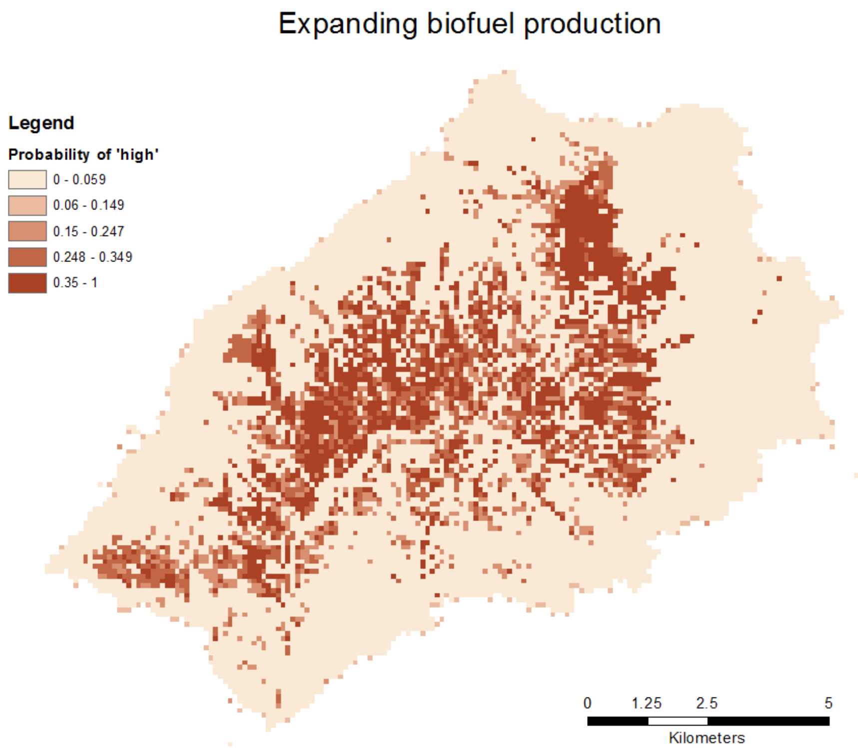


Figure 30 Expansion of biofuel production

The ecosystem service co-benefits of expanding biofuel production are very similar to those for expanded timber production; this reflects the similar constraints on this scenario. The exception is that this scenario allows expansion on to pasture. As such, the area of co-benefits is larger, but care is required in interpretation as this may not be the same type of biofuel crop, e.g. timber for firewood versus energy crops. Actual ecosystem service outcomes would be influenced by type of biofuel, management of woodland, and stage in the lifecycle of the biofuel production. Water provisioning (Figure 31) also shows a higher weighting placed on mist capture above 690m. Moderating runoff may also be important and will also contribute to flood risk reduction (Figure 32). The potential for carbon sequestration (Figure 33) reflects biomass growth although the carbon accounting potential will need to reflect lifecycle and eventual use as fuel. The potential for recreation or other cultural services (Figure 34) is estimated in the same way as for woodland, however this may be particularly dependent on the type of biofuel crop and management approach.

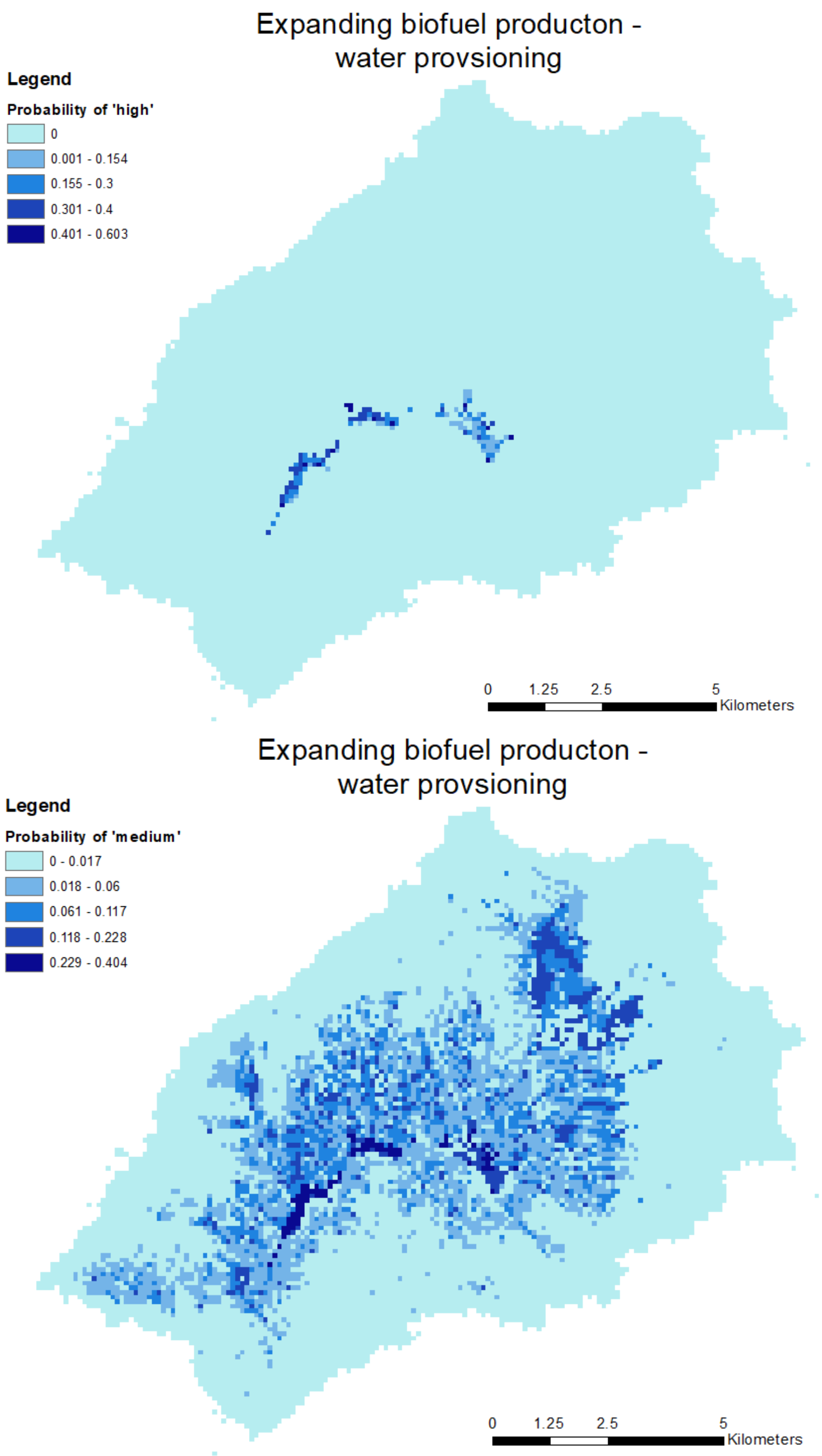


Figure 31 Expanding biofuel production – water provisioning, probability of 'high' and 'medium'

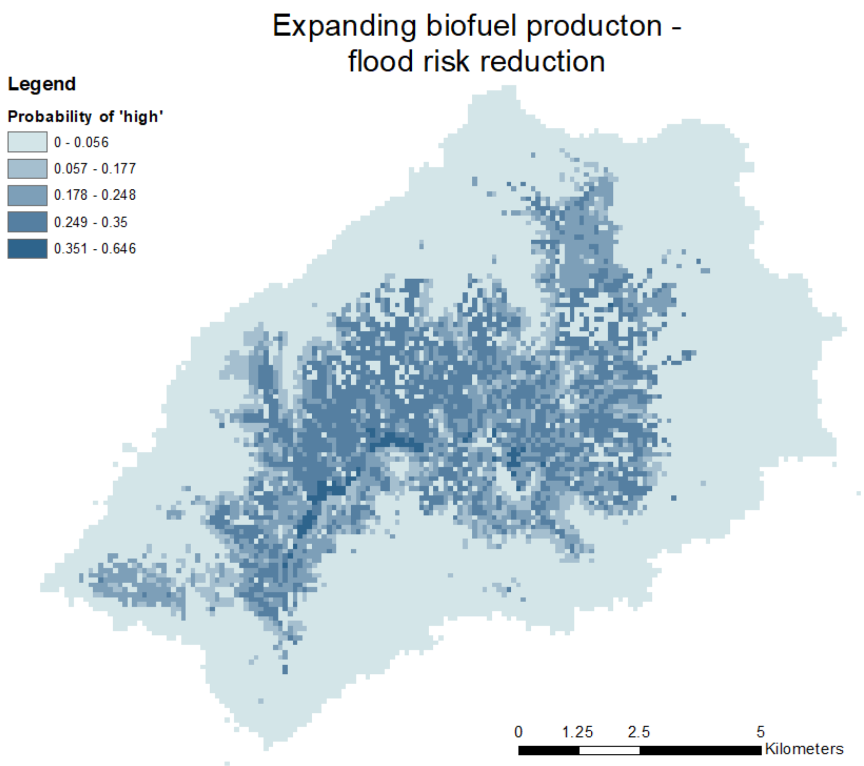


Figure 32 Expanding biofuel production – flood risk reduction

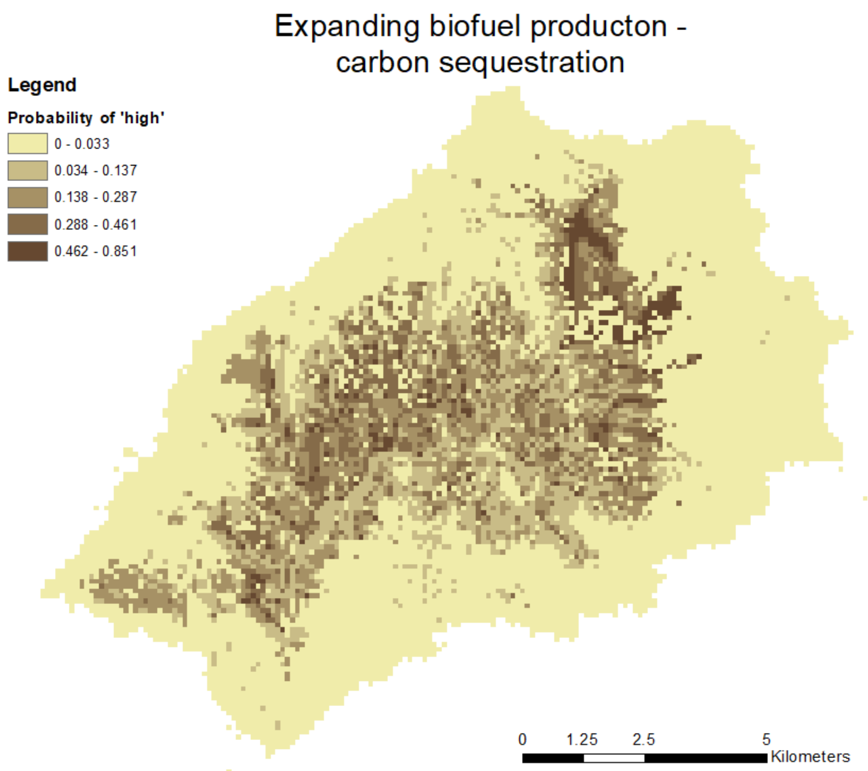
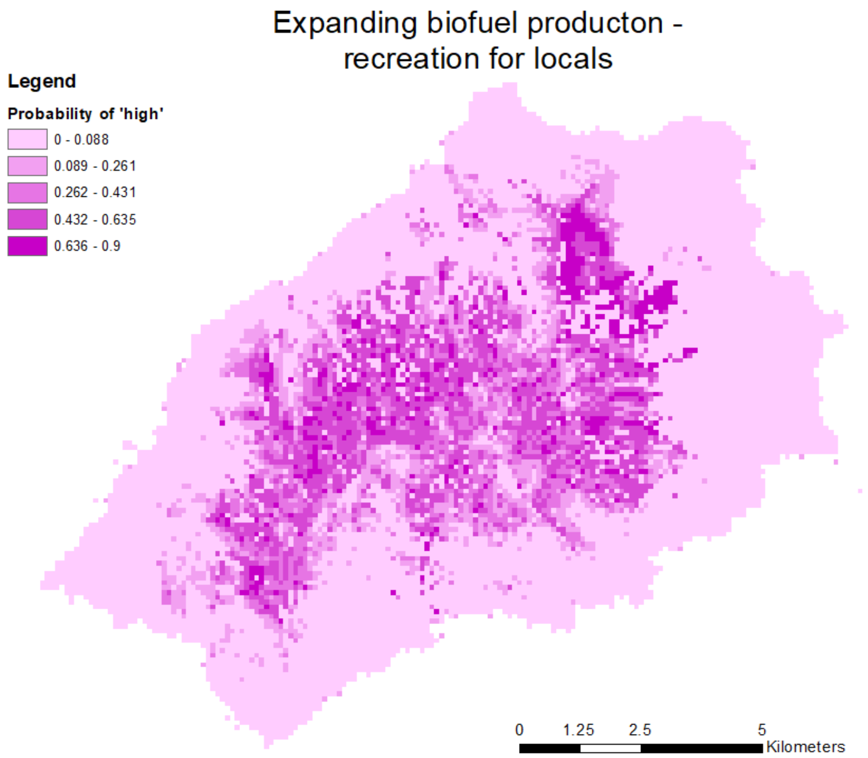


Figure 33 Expanding biofuel production – carbon sequestration



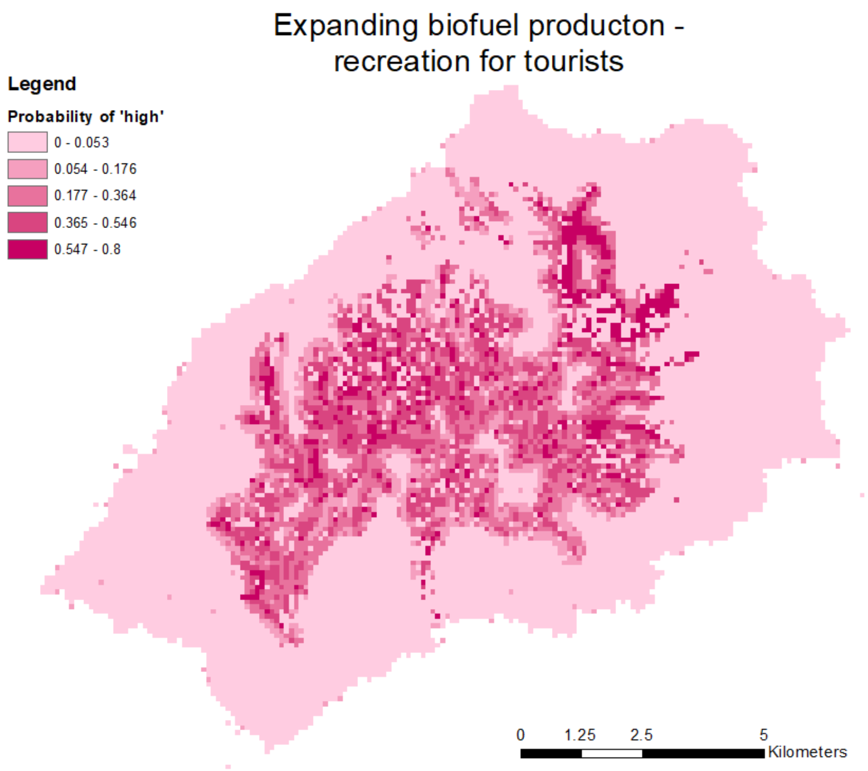


Figure 34 Expanding biofuel production – recreation for locals and tourists

5.4. Replacement of flax

This scenario considered the replacement of flax with either forestry or the restoration of native habitats. Figure 35 shows the contrast between flax and native habitats at Diana's Peak (the boundary between the two is a footpath). The forestry element of the scenario is already included in the preceding scenarios on timber and biofuels, this scenario restricts that change to areas of flax. The same constraints of accessibility (slope and distance to roads) are applied to forestry as in the previous scenarios, but not to the alternative option of native habitat restoration.

The results of these two options for flax replacement are presented together to allow easier comparison between them. The potential areas for replacement of flax are illustrated in Figure 36, the constraints on forestry indicate that a smaller area would be suitable for this land use than for native habitat recreation. This may also have important implications for biodiversity, as native habitats offer the potential for a more connected habitat.

The water provisioning potentials are illustrated in Figure 37. These are very similar across the two options, but the probability of the state being ‘high’ is higher for native habitats. The main driver is altitude and the suitability for mist capture. Both options may perform similarly in the model, but the wider potential for native habitats is likely to the reason for the better performance.

Flood risk reduction is presented in Figure 38. The spatial extent of the benefits are similar for each option, but native habitats perform better in terms of the probability of the state being ‘high’. The potential benefits appear to be more localised for native habitats restoration, specifically along the higher ridges such as Diana’s Peak. This reflects the better suitability of that area for native habitats (slope etc.). However, it also indicates where care is needed in interpreting the BN outputs. Habitats can contribute to flood risk reduction in a number of ways: vegetation can slow down water through interception, evaporation, reducing runoff rates through surface roughness, and improving soil infiltration. The contribution of each of these processes will differ according to context. Vegetation, whether introduced or semi-natural, on the higher, steeper slopes may not perform as well as that lower down in slowing water. The total combined precipitation and runoff received may be lower, so there is less water to slow down. Conversely, the areas of forestry indicated on shallower slopes may receive a higher combined precipitation and runoff, so although appearing to perform less well, they provide a greater service. They may also be closer to the receptors of flood water so the benefits they provide may be higher. The BN does not fully account for these contextual variations, so local knowledge and judgement should be used to interpret the outputs.

Figure 39 illustrates the carbon sequestration potential of the two options. The performance of each is very similar, although the probability of ‘high’ for native habitats is distributed more towards the higher end of the probability scale. Actual performance would depend on the species mix used for each option and their relative potentials to increase biomass. Arguably, production related to forestry may outperform native vegetation at least in the short-term, and may be better placed to exploit carbon market opportunities.

The recreational potentials for local residents and tourists are illustrated in Figure 40 and Figure 41 respectively. As with the results in section 4.3 the term ‘recreation’ covers a wide set of cultural services rather than specific forms of recreation[16]. The performance of each option is similar for both types of user, but the probabilities of ‘high’ tend to be greater for native habitats, these are also more concentrated along the higher ridges. This area also corresponds with existing footpaths.

[16] Under the CICES system these would be ‘experiential interactions’

Figure 35 Flax (lower) and native vegetation (upper) at Diana's Peak (source: McVittie)

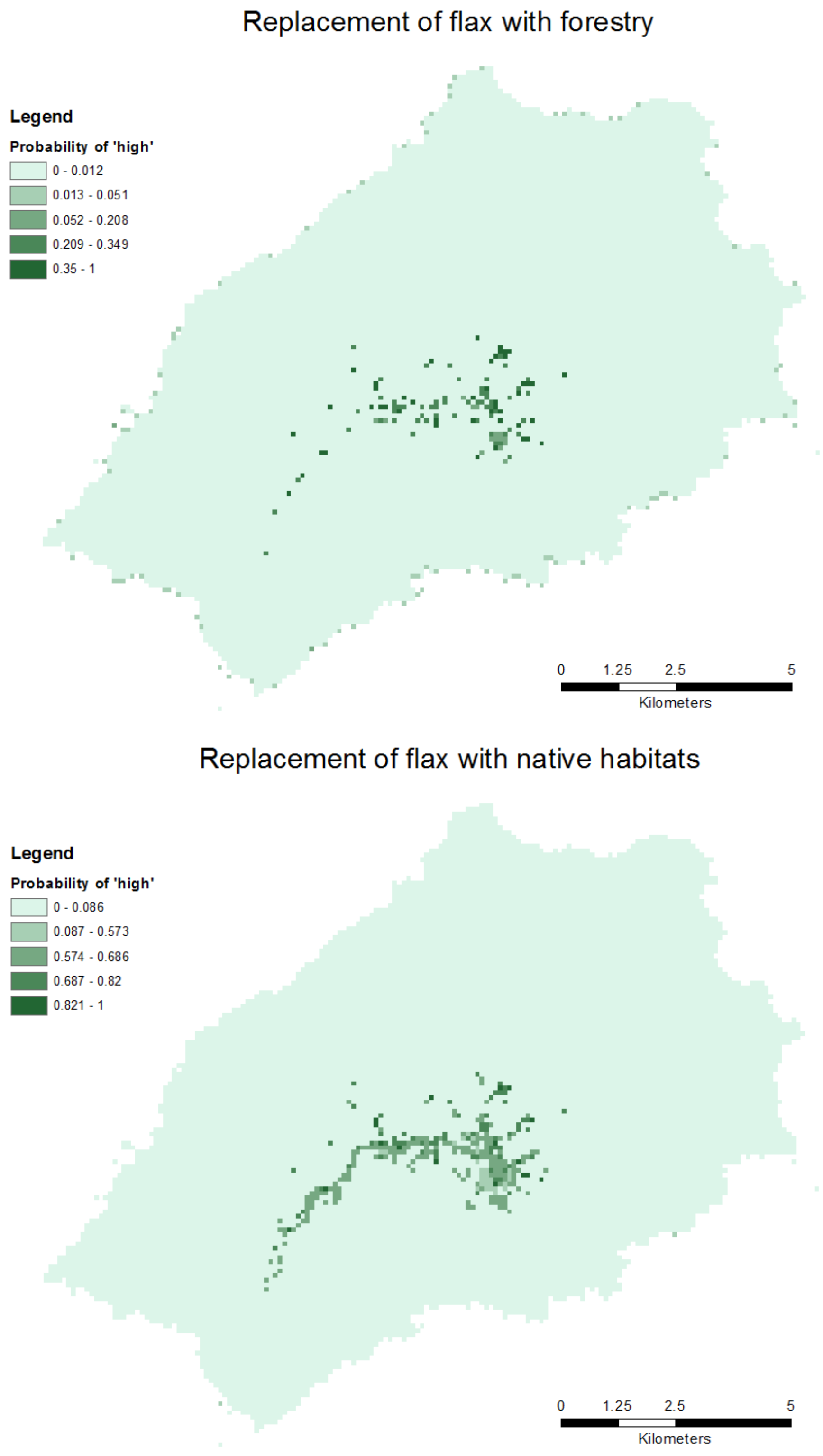
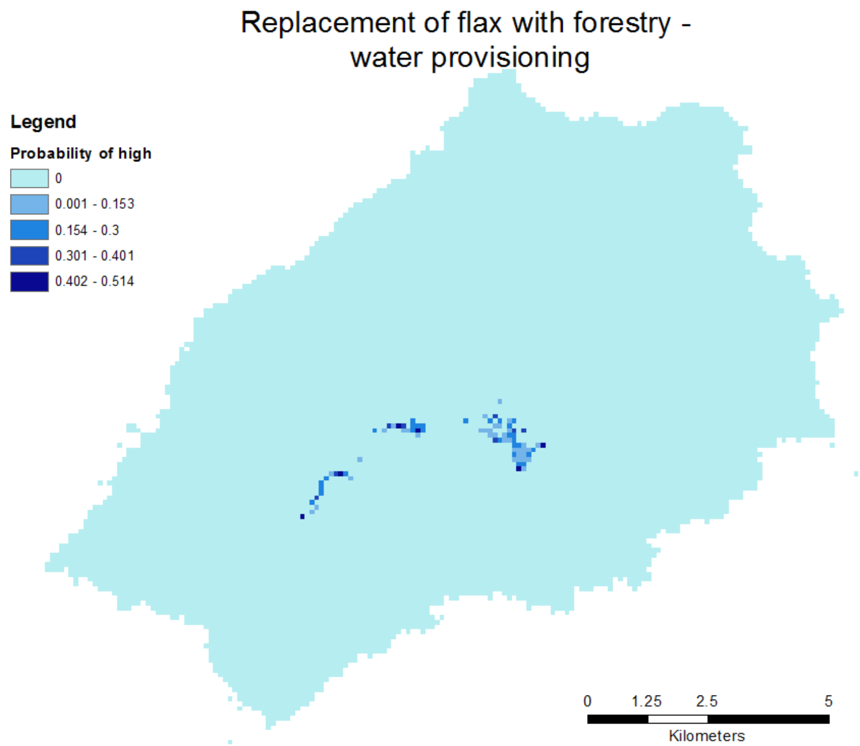


Figure 36 Replacement of flax with forestry and native habitats



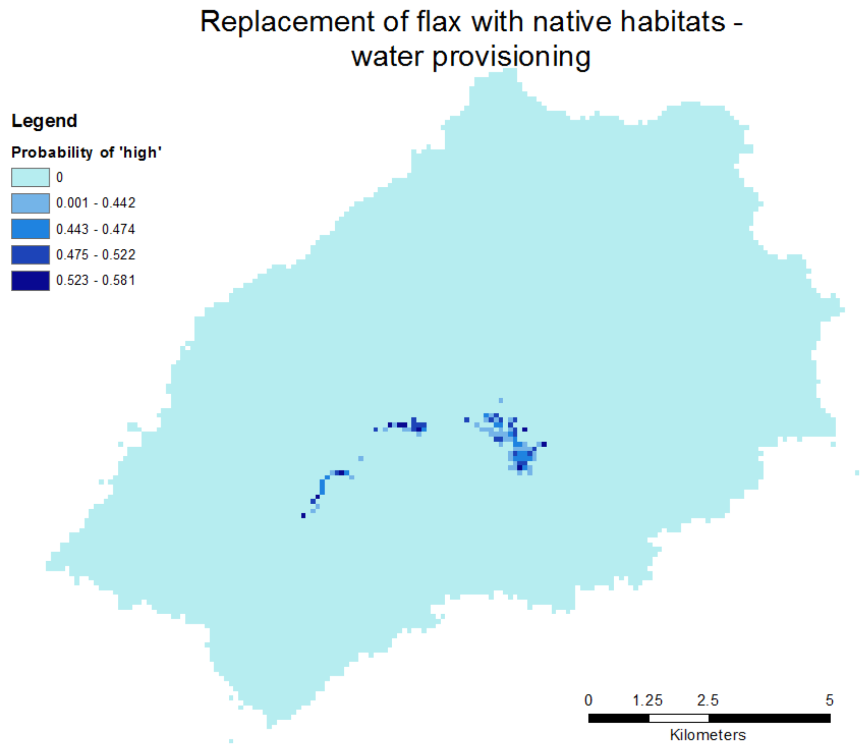
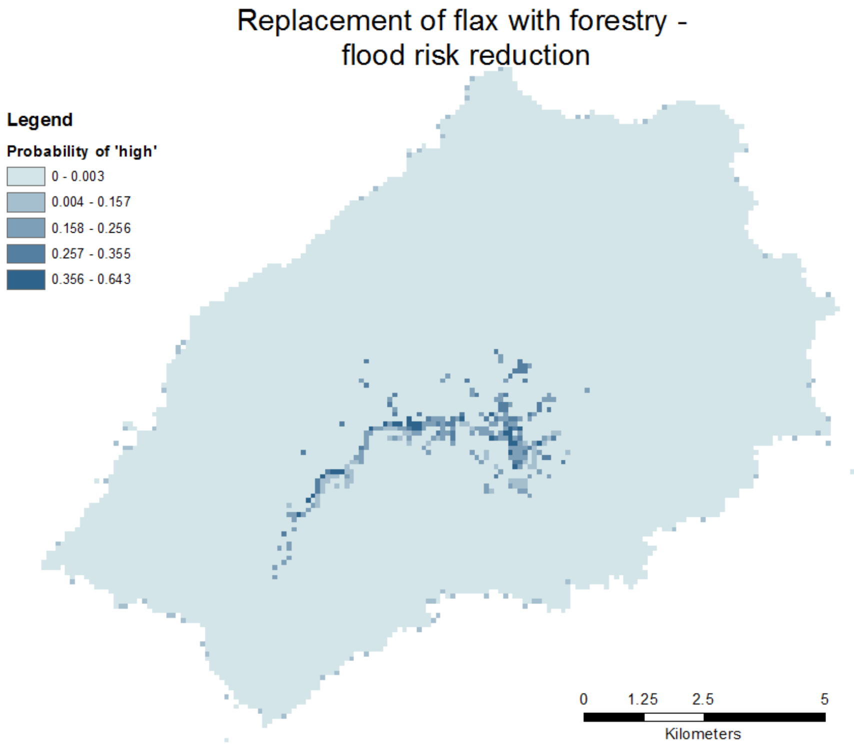


Figure 37 Replacing flax with forestry or native habitats – water provisioning



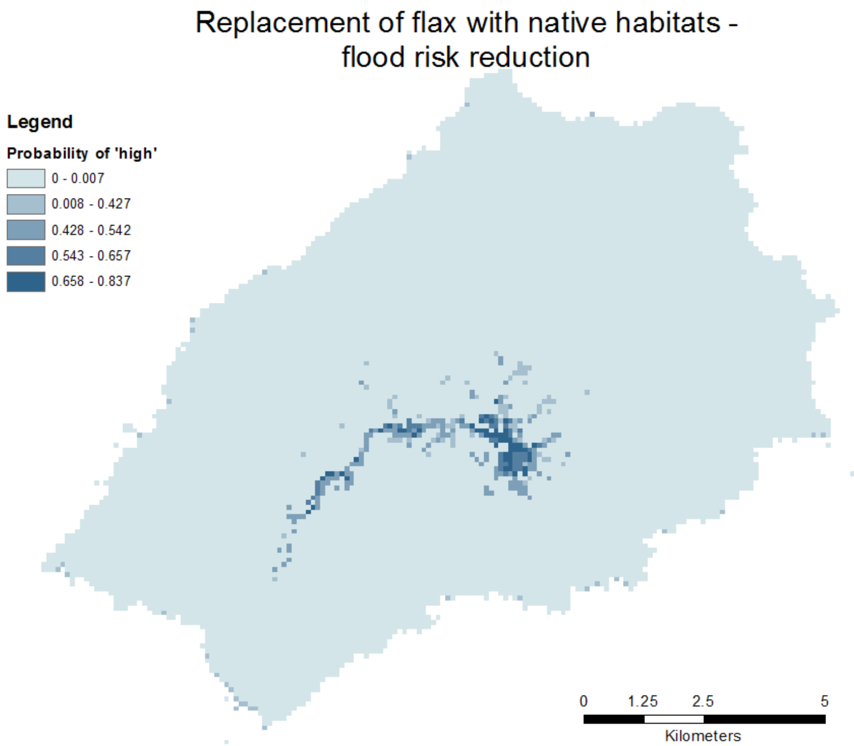
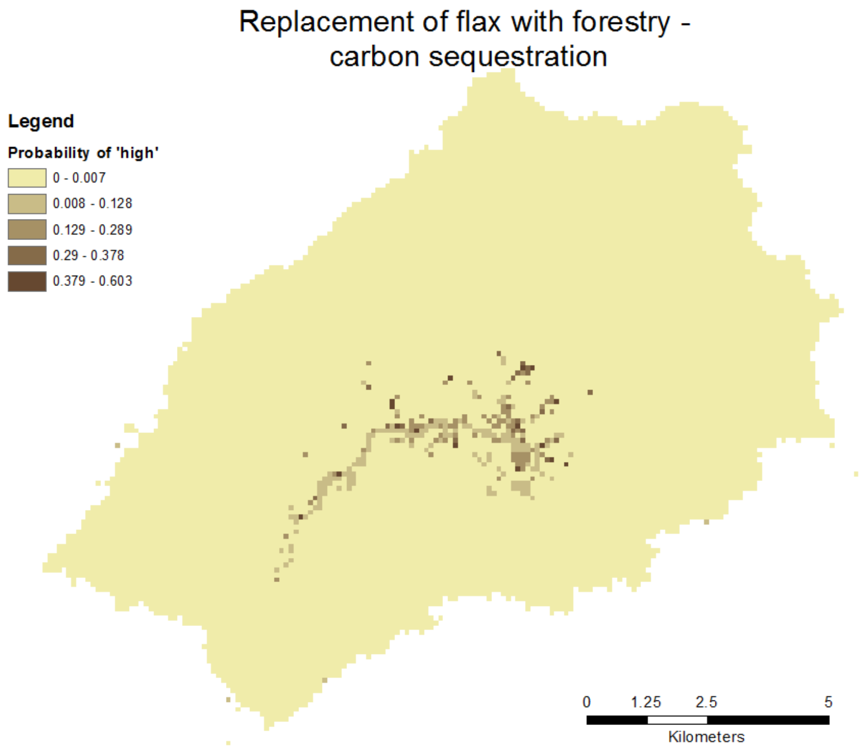


Figure 38 Replacing flax with forestry or native habitats – flood risk reduction



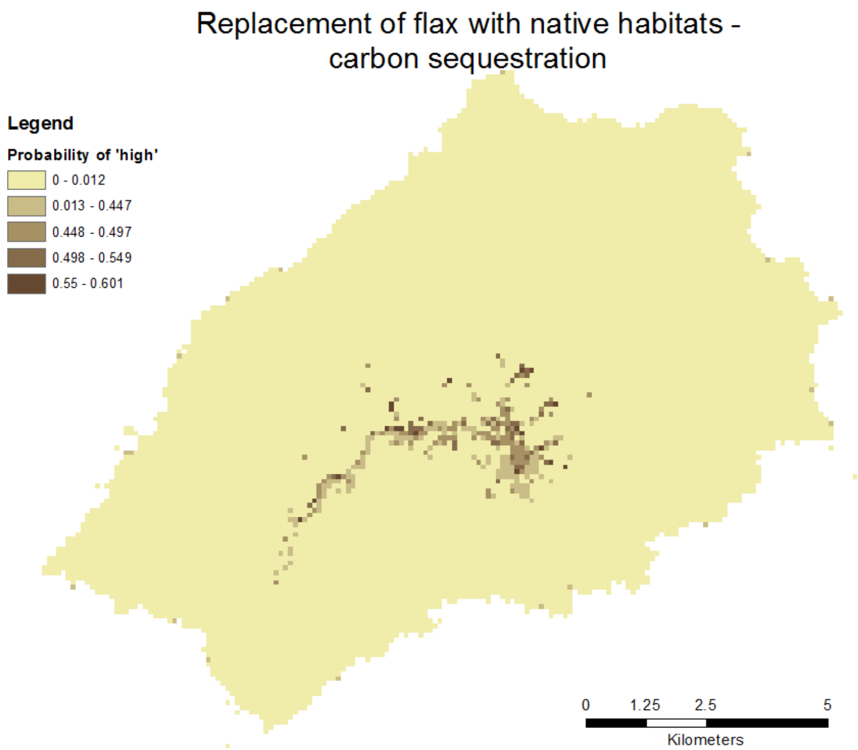
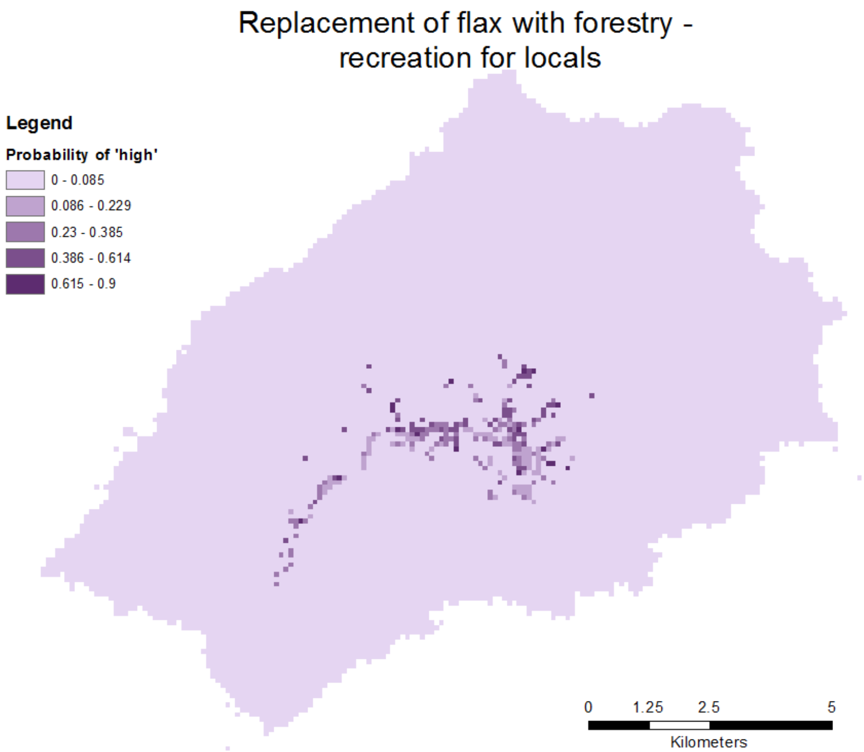


Figure 39 Replacing flax with forestry or native habitats – carbon sequestration



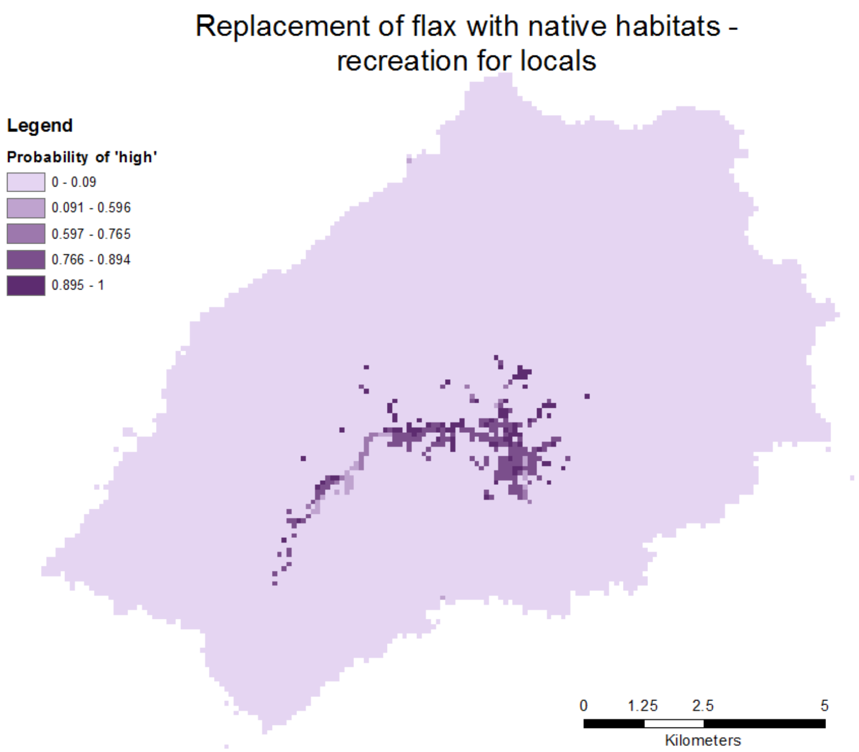
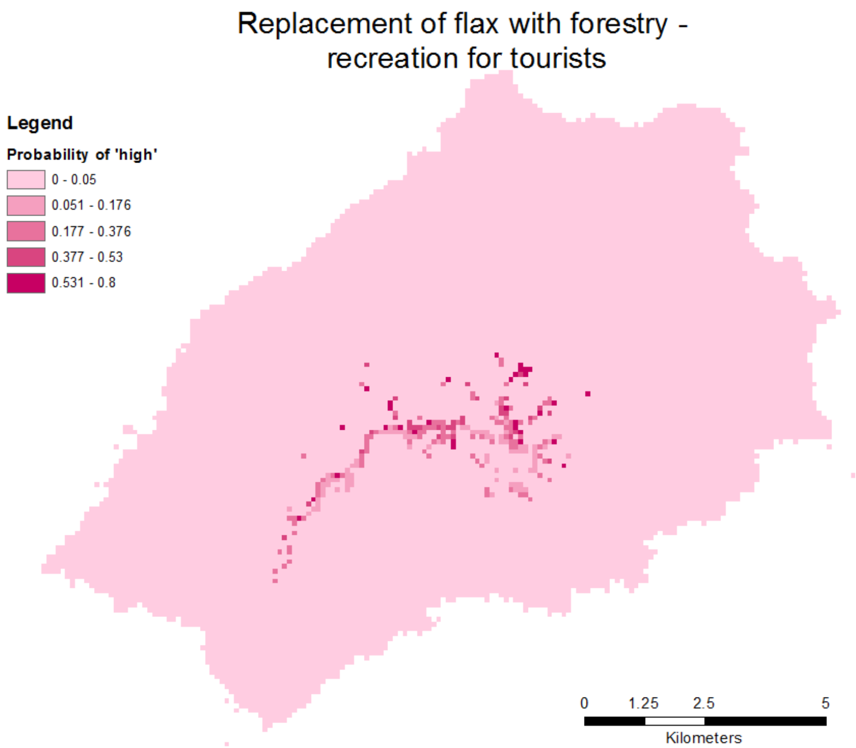


Figure 40 Replacing flax with forestry or native habitats – recreation for local residents



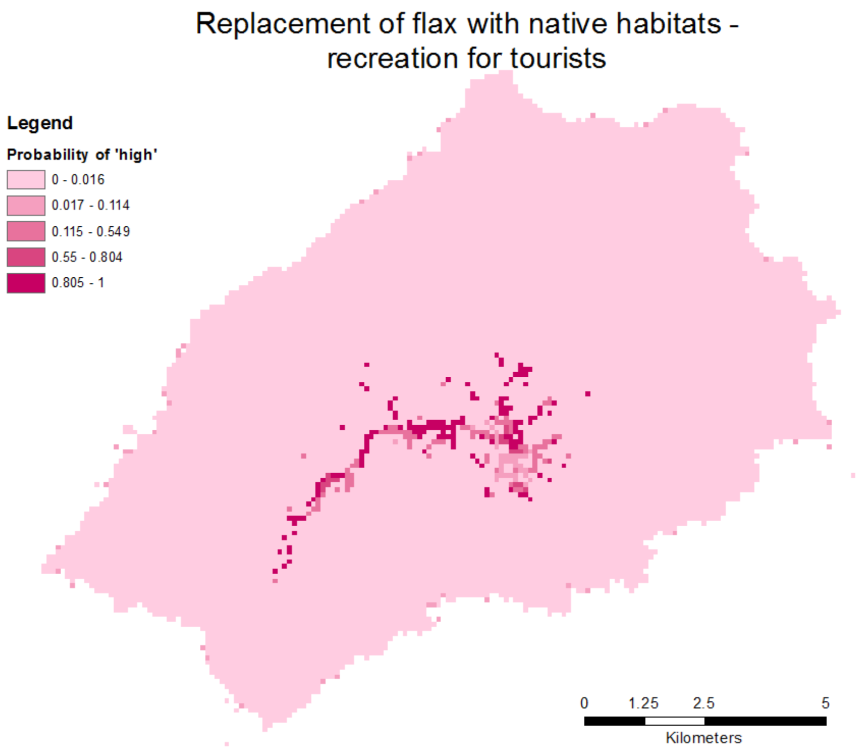


Figure 41 Replacing flax with forestry or native habitats – recreation for tourists

5.5. Expansion of development

The final scenario considers areas suitable for expanded development. The model constrains suitable areas to introduced and 'other' habitats with the exception of land used for horticulture, plantations or rural gardens. Further constraints are based on accessibility in terms of slope and proximity to roads. Sites of existing built development including the airport are not explicitly mapped in the land cover layer so have not been excluded from the scenario. The results, illustrated in Figure 42, show there is considerable scope for development, however much of the indicated area is already developed. Other indicated areas may be unsuitable for practical reasons such as water supply, or land ownership and tenure. A large part of the suggested development area also lies within National Conservation Areas. National Conservation Area boundaries were not included as a BN input, this illustrates the need to ground truth BN outputs. The results do show that development could be distributed across the island if these issues are surmountable.

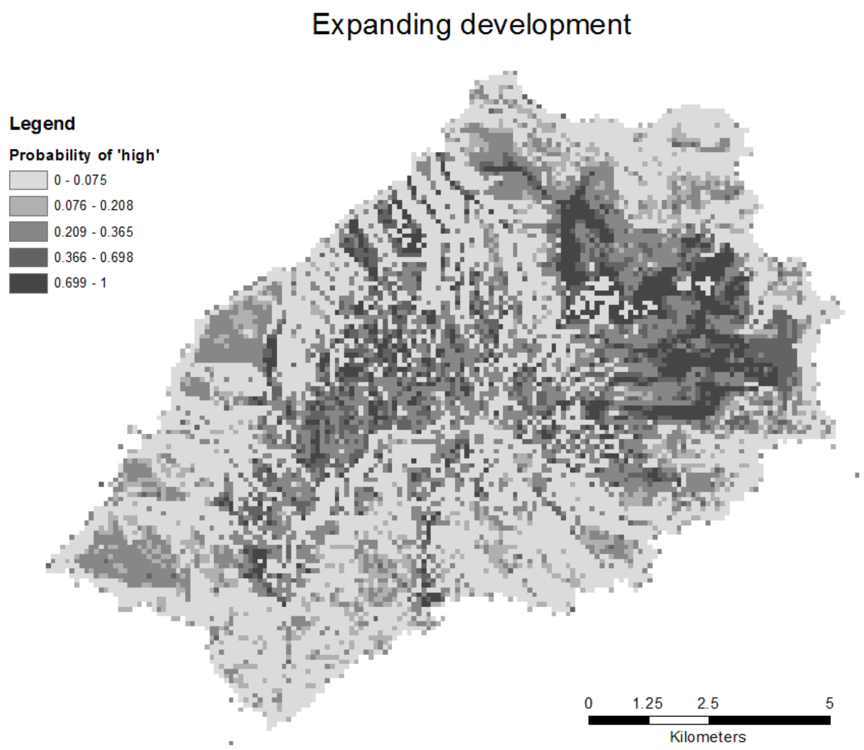


Figure 42 Expanding development

6. Discussion and summary

In this section we summarise the key messages from the BN and scenario results. We then consider the limitation of the approach and our analysis. This is a reflective critique and is intended to provide context for the interpretation of the model. Finally, we discuss how the BN will be made available for wider analysis in the future, specifically through the development of user interface.

6.1. Summary of outcomes

We have used the BN to explore both the current natural capital configuration of St Helena based on habitats and biophysical characteristics, and potential future configurations that could arise from future economic scenarios. The latter included both opportunity mapping and an ecosystem services assessment.

As would be expected the potential for provisioning services closely reflected the land cover type. The potential for these services is constrained by abiotic characteristics such as a slope. Conversely, water provisioning is not directly linked to a specific land use and arises from an interaction of other characteristics such as slope and altitude. Land use is arguably a secondary moderator of the service rather than a primary driver. Precipitation, whether rain or mist, increases with altitude. Lower gradients combined with vegetation type can help to reduce runoff rate increasing the opportunity for water collection. The BN indicated where that potential might be highest. The regulating service of flood risk reduction relies on similar interactions to water supply, although the impact is inverted reflecting precipitation patterns, lower precipitation being associated with both lower water provision and lower flood risk, i.e. there is less scope for that risk to be reduced which is the service.

The other regulating services, pollination and carbon sequestration are primarily driven by land use and habitats. The former relies on being surrounded by more complex or varied habitats. The latter, is associated with land uses such as forestry that accumulate biomass.

Our modelling of cultural services relates to recreational potential, this we linked primarily to accessible woodland habitats both introduced and native. These corresponded reasonably well with survey and social media analysis of cultural services. A more in-depth analysis of the woodland species and management approach (i.e. intensity) might be informative in better reconciling our results with the cultural services study.

We assessed a number of land use change scenarios that were identified from workshops on future economic scenarios for St Helena. Despite the different emphases of each economic scenario, there were a number of commonalities. Expanding provisioning of both food, timber and biofuel was of interest either to meet increasing demand, including for export markets, or to reduce dependence on imports. Our analysis indicated where there were opportunities for expansion. A wider set of ecosystem service co-benefits were also considered for woodland scenarios (timber and biofuel). The output maps have the potential to better inform land use decisions by highlighting where trade-offs and synergies exist across different management and policy objectives.

We also assessed options for replacing flax with either productive timber or native vegetation. Both options resulted in an increase in ecosystem services, however there was greater potential with respect to native vegetation. This may reflect that the best opportunities to replace flax with timber have already been identified, and that constraints such as slope and access offer more limited future opportunities.

6.2. Limitations

Despite its flexibility, there are a number of limitations with the modelling approach used in this study. An important benefit of the BN approach is that it does not require the functional relationships between nodes to be fully quantified. For example, we do not need to know how slope and rainfall volumes interact to produce a given level of runoff. This is advantageous as we can apply the model across a range of contexts where a strictly defined functional relationship may not hold, e.g. adding vegetation and soil types as further influences on runoff. The complexity of the modelling task is therefore kept to a manageable level. However, this does mean that the output from the BN relate to broadly defined states (high, medium, low) not specific quantities. This reduces the ability to make comparisons across outputs or to assess trade-offs between different ecosystem services or scenarios.

An early ambition for the BN model was to integrate economic values with the outputs. As the process progressed, it became apparent that this would not be possible in a defensible way. Economic valuation of an ecosystem service requires the identification of both the level of supply and the demand or beneficiaries for the service. The extent that this is possible will vary across different ecosystem services. For provisioning services such as food the model outcomes could be interpreted as the potential productivity of different habitat patches used of horticulture, pasture or plantations. That productivity would need to be linked to production, i.e. types of crops or livestock, which could then have an economic value applied. For water provisioning, the model does not include information on volumes, either inputted into the system (precipitation) or available for supply to users. The spatial aspect of the model also means that pixels that appear to perform well may not be contributing to final water supply as they are in catchments with little or no impoundment. Similarly, pixels showing high potential for flood risk reduction may not be upstream of vulnerable properties.

The value of pollination services will range according to the final use of what is being pollinated, this could be valuable food crops or private gardens that provide cultural services. Carbon sequestration, is unique among the ecosystem services, as the benefit provided is independent of spatial location, i.e. the value of the benefit does vary with proximity to beneficiaries. The difficulty of valuing carbon sequestration arises from lack of quantification. Additional analysis could link predicted productivity levels from the BN to the carbon sequestration potential for the habitat type in each pixel.

The recreational benefits of different habitats and scenarios would be derived from the actual use by residents and visitors on St Helena. Although we can predict the potential for those benefits to be provided by a pixel of habitat, the BN does not predict use. The broad definition of recreation also means that a variety of value types might be appropriate. Monetary values based on travel costs and other expenditure may be appropriate for tourists. Health benefits may also be valued in monetary terms although attribution to a particular habitat or site is problematic. Improved well-being through recreation and interaction with nature is a further important benefit, but is difficult to express in monetary terms.

These difficulties in quantification in physical and economic terms are linked to a further limitation of the current BN model. Essentially the BN outputs are the combination of a large number of independent BNs run for each of the pixels that comprise the land cover map of St Helena. The relationships between these pixels is not accounted for[17]. This is particularly relevant where ecosystem services rely on processes that flow across pixels, e.g. water provisioning and flood regulation. Linked to these interactions are sizes of habitat patches or their place within a wider network. Patch size and connectivity might also be important for some types of recreation and pollination services. It might be possible to capture some of these relationships in a more focused BN,

[17] The ‘pollination’ node is the only one that includes influences from natural capital outside the pixel being assessed through the ‘landscape biodiversity’ node. This is also static in the sense that the ‘landscape biodiversity’ does not change in response to scenarios. This is an example of the lack of feedback inherent in BNs.

e.g. within a defined catchment, where the structure and progression through nodes reflects both the ecosystem services cascade and biophysical flows. This would have to be more context specific, and would lose the generality of the model developed for St Helena. Arguably, process based models would be more appropriate, but would require considerably more development effort.

The 1 ha pixel size is arguably quite coarse for decision making at island or sub-island scales such as on St Helena. It means that fine grain details are not included in the input maps and are not represented in the outputs. This reflects a trade-off between model resolution and the processing time required to estimate the model. Ultimately, the BN is intended to guide decision-making and ground-truthing of results will always be advisable as the model will always be a simplification of reality.

6.3. Developing a user interface

The full St Helena natural capital BN model requires considerable time to run, particularly when evaluating different scenarios. Users would also need to adapt both the BN model (Annex 1) and the R code for the bnspatial package (Annexes 2 and 3). To make the BN more accessible and to reduce computation time, it would be useful to have a more user-friendly interface that allows smaller, more defined, changes in habitats and land use to be evaluated.

JNCC are currently developing a web-app user interface, using the R package “Shiny”. The interface will enable users to make changes to the land cover map, then re-run the BN using the new land cover to evaluate the impacts on service provision. As demonstrated above, the network in its current form can generate opportunity maps for expansion of different land uses or land cover types. The user interface will go beyond this by allowing users to model the impacts of those land use changes on all services assessed by the BN, and therefore to better understand the trade-offs associated with any theoretical future land use change. This has obvious potential applications for use in planning, both for assessing individual proposals and at a strategic level such as for informing land development control plans. Figure 43 shows a screenshot of the prototype user interface. JNCC are aiming to have a fully functional prototype by summer 2019.

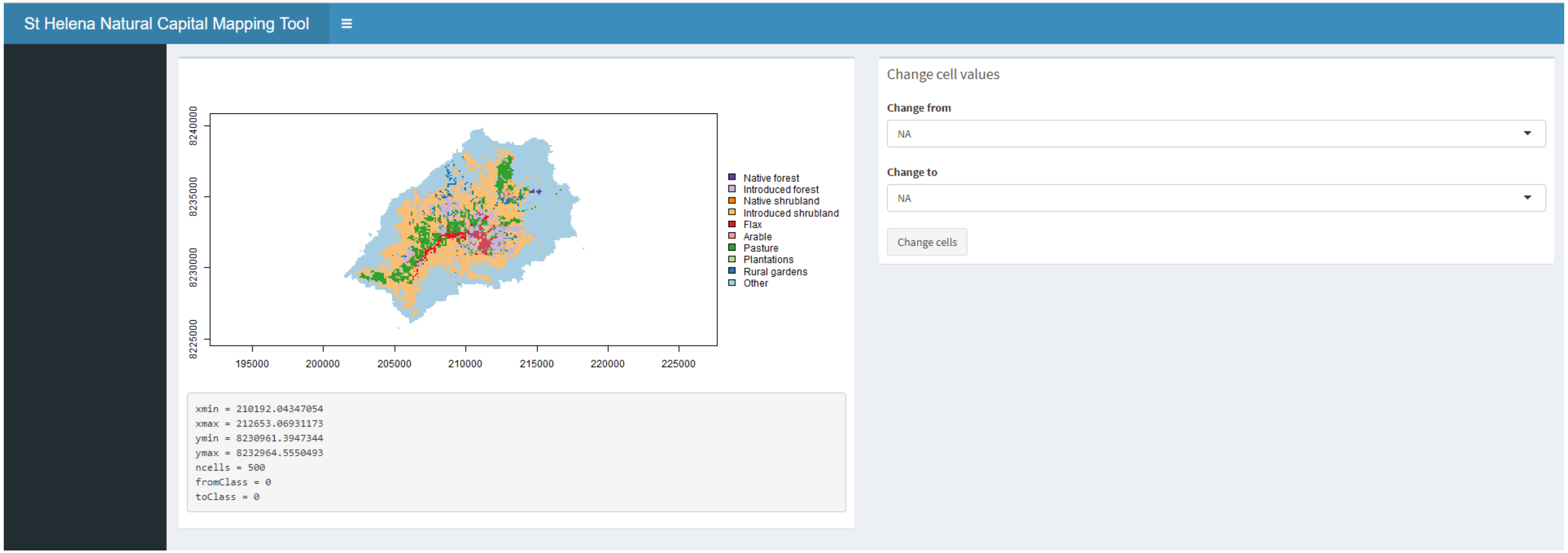


Figure 43 Screenshot of R Shiny interface

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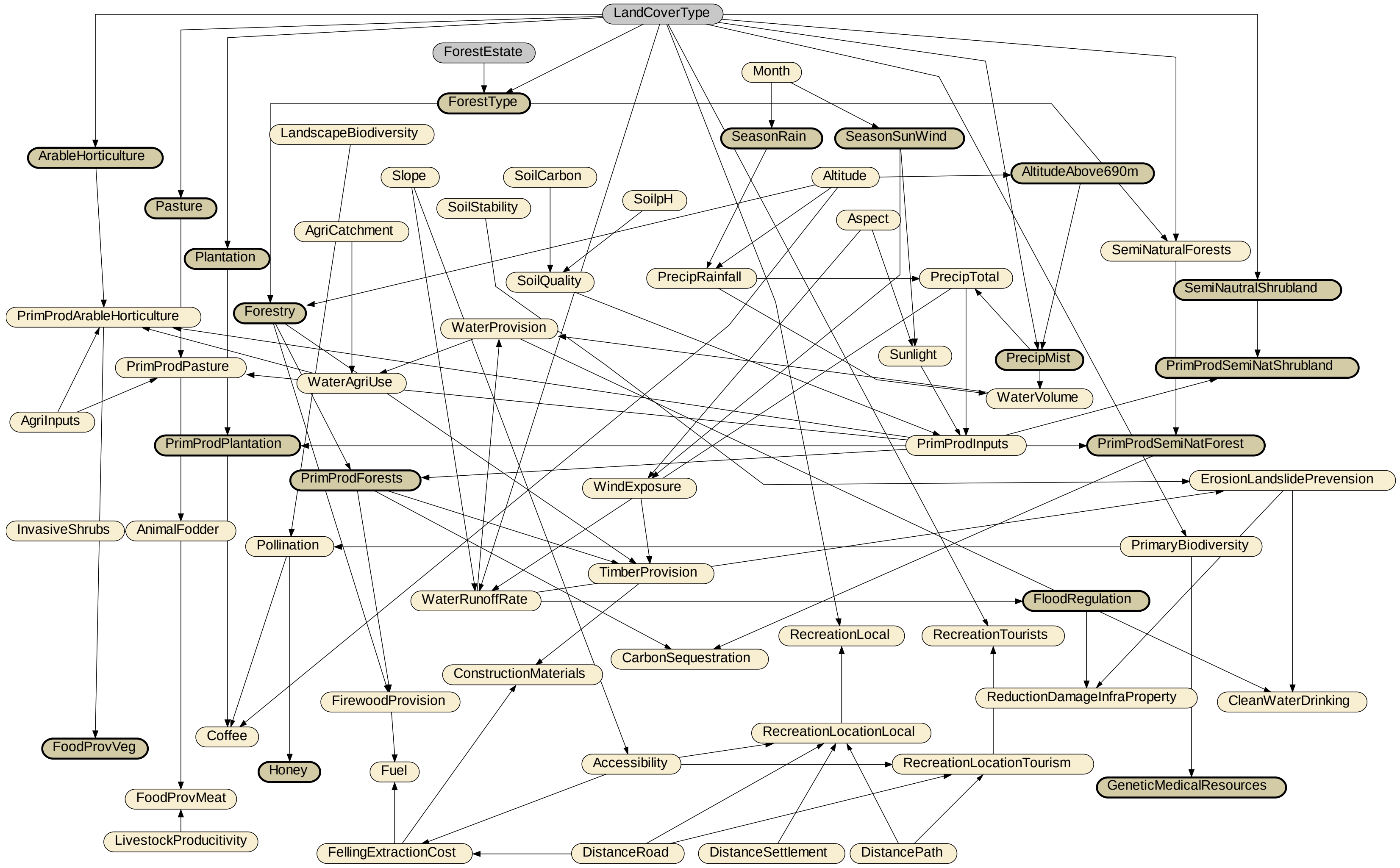
Annex 1: Full network model

The diagram of the final BN model used to estimate the results presented in section 4 is reproduced on the following page.


LandCoverType
ForestEstate
Month
ForestType
SeasonRain
SeasonSunWind
LandscapeBiodiversity
ArableHorticulture
Slope
SoilCarbon
Altitude
AltitudeAbove690m
SoilpH
SoilStability
Pasture
Aspect
AgriCatchment
SemiNaturalForests
Plantation
SoilQuality
PrecipRainfall
PrecipTotal
SemiNautralShrubland
PrimProdArableHorticulture
Forestry
WaterProvision
Sunlight
PrecipMist
PrimProdSemiNatShrubland
PrimProdPasture
WaterAgriUse
WaterVolume
AgriInputs
PrimProdPlantation
PrimProdInputs
PrimProdSemiNatForest
PrimProdForests
WindExposure
ErosionLandslidePrevension
InvasiveShrubs
AnimalFodder
Pollination
PrimaryBiodiversity
TimberProvision
WaterRunoffRate
FloodRegulation
RecreationLocal
RecreationTourists
CarbonSequestration
ConstructionMaterials
FirewoodProvision
ReductionDamageInfraProperty
CleanWaterDrinking
Coffee
RecreationLocationLocal
FoodProvVeg
Honey
Fuel
Accessibility
RecreationLocationTourism
GeneticMedicalResources
FoodProvMeat
LivestockProducitivity
FellingExtractionCost
DistanceRoad
DistanceSettlement
DistancePath

Annex 2: R code for bnspatial analsys

The R code for the bnspatial model is reproduced below. Note that a generic file path (C:/filepath) has been included

```
library(sp)
library(raster)
library(rgdal)
library(bnspatial)

setwd("C:/filepath")
list.files(pattern = "\\.tif")

#import files as Raster file
a_raster <- raster("Altitude.tif")
b_raster <- raster("Aspect.tif")
c_raster <- raster("DistanceFromPath.tif")
d_raster <- raster("DistanceFromRoad.tif")
e_raster <- raster("DistanceFromSettlement.tif")
f_raster <- raster("ForestEstate.tif")
g_raster <- raster("LandCoverType.tif")
h_raster <- raster("LandscapeBiodiversity.tif")
i_raster <- raster("Slope.tif")
l_raster <- raster("SoilCarbon.tif")
m_raster <- raster("SoilpH.tif")
n_raster <- raster("SoilStability.tif")

#check extents
extent(a_raster)
extent(b_raster)
extent(c_raster)
extent(d_raster)
extent(e_raster)
extent(f_raster)
extent(g_raster)
extent(h_raster)
extent(i_raster)
extent(l_raster)
extent(m_raster)
extent(n_raster)

#check resolution
res(a_raster)
res(b_raster)
res(c_raster)
res(d_raster)
res(e_raster)
res(f_raster)
res(g_raster)
```

```
res(h_raster)
res(i_raster)
res(l_raster)
res(m_raster)
res(n_raster)

#CHECK LEVELS
va <- as.factor(raster::getValues(a_raster))
vb <- as.factor(raster::getValues(b_raster))
vc <- as.factor(raster::getValues(c_raster))
vd <- as.factor(raster::getValues(d_raster))
ve <- as.factor(raster::getValues(e_raster))
vf <- as.factor(raster::getValues(f_raster))
vg <- as.factor(raster::getValues(g_raster))
vh <- as.factor(raster::getValues(h_raster))
vi <- as.factor(raster::getValues(i_raster))
vl <- as.factor(raster::getValues(l_raster))
vm <- as.factor(raster::getValues(m_raster))
vn <- as.factor(raster::getValues(n_raster))
levels(va)
levels(vb)
levels(vc)
levels(vd)
levels(ve)
levels(vf)
levels(vg)
levels(vh)
levels(vi)
levels(vl)
levels(vm)
levels(vn)

#IMPORT NETWORK
network <- loadNetwork('StH_BBN_final_190409_scenarios.net')
network
networkscenario <- loadNetwork('StH_BBN_final_190409_scenarios.net')
networkscenario

#create a list with the independent spatial variables
spatialData <- c(a_raster, b_raster, c_raster, d_raster, e_raster, f_raster, g_raster, h_raster, i_raster,
l_raster, m_raster, n_raster)
class(spatialData)
names(spatialData)
spatialData

#using a lookup table where nodes names are without spaces
#lookup is a list which contains three columns that define the data states (classes), the numeric values
and whether or not they are categorical
```

```
#the table links properly the nodes from the network to the spatial data in input
lookup <- 'lookup_table_short.txt'
names(lookup)
class(lookup)
intervals_lk <- importClasses(lookup)
names(intervals_lk)
class(intervals_lk)
intervals_lk

#set the target
target1 <-'FoodProvMeat'
target2 <- 'FoodProvVeg'
target3 <- 'CarbonSequestration'
target4 <- 'Coffee'
target5 <- 'Honey'
target6 <- 'Fuel'
target7 <-'ConstructionMaterials'
target8 <- 'RecreationLocal'
target9 <- 'RecreationTourists'
target10 <-'GeneticMedicalResources'
target11 <- 'ReductionDamageInfraProperty'
target12 <- 'WaterProvision'
target13 <- 'PrimProdInputs'

#run the bnspatial for class and entropy
bnt1 <- bnspatial(network, target1, spatialData, intervals_lk, msk=a_raster)
bnt2 <- bnspatial(network, target2, spatialData, intervals_lk, msk=a_raster)
bnt3 <- bnspatial(network, target3, spatialData, intervals_lk, msk=a_raster)
bnt4 <- bnspatial(network, target4, spatialData, intervals_lk, msk=a_raster)
bnt5 <- bnspatial(network, target5, spatialData, intervals_lk, msk=a_raster)
bnt6 <- bnspatial(network, target6, spatialData, intervals_lk, msk=a_raster)
bnt7 <- bnspatial(network, target7, spatialData, intervals_lk, msk=a_raster)
bnt8 <- bnspatial(network, target8, spatialData, intervals_lk, msk=a_raster
bnt9 <- bnspatial(network, target9, spatialData, intervals_lk, msk=a_raster)
bnt10 <- bnspatial(network, target10, spatialData, intervals_lk, msk=a_raster)
bnt11 <- bnspatial(network, target11, spatialData, intervals_lk, msk=a_raster)
bnt12 <- bnspatial(network, target12, spatialData, intervals_lk, msk=a_raster)
bnt13 <- bnspatial(network, target13, spatialData, intervals_lk, msk=a_raster)

writeRaster(bnt1$Class,"C:/filepath/FoodProvMeat_class.tif", overwrite=TRUE)
writeRaster(bnt1$Entropy,"C:/filepath/FoodProvMeat_entropy.tif", overwrite=TRUE)

writeRaster(bnt2$Class,"C:/filepath/FoodProvVeg_class.tif", overwrite=TRUE)
writeRaster(bnt2$Entropy,"C:/filepath/FoodProvVeg_entropy.tif", overwrite=TRUE)

writeRaster(bnt3$Class,"C:/filepath/CarbonSequestration_class.tif", overwrite=TRUE)
writeRaster(bnt3$Entropy,"C:/filepath/CarbonSequestration_entropy.tif", overwrite=TRUE)
```

```
writeRaster(bnt4$Class,"C:/filepath/Coffee_class.tif", overwrite=TRUE)
writeRaster(bnt4$Entropy,"C:/filepath/Coffee_entropy.tif", overwrite=TRUE)

writeRaster(bnt5$Class,"C:/filepath/Honey_class.tif", overwrite=TRUE)
writeRaster(bnt5$Entropy,"C:/filepath/Honey_entropy.tif", overwrite=TRUE)

writeRaster(bnt6$Class,"C:/filepath/Fuel_class.tif", overwrite=TRUE)
writeRaster(bnt6$Entropy,"C:/filepath/Fuel_entropy.tif", overwrite=TRUE)

writeRaster(bnt7$Class,"C:/filepath/ConstructionMaterials_class.tif", overwrite=TRUE)
writeRaster(bnt7$Entropy,"C:/filepath/ConstructionMaterials_entropy.tif", overwrite=TRUE)

writeRaster(bnt8$Class,"C:/filepath/RecreationLocal_class.tif", overwrite=TRUE)
writeRaster(bnt8$Entropy,"C:/filepath/RecreationLocal_entropy.tif", overwrite=TRUE)

writeRaster(bnt9$Class,"C:/filepath/RecreationTourists_class.tif", overwrite=TRUE)
writeRaster(bnt9$Entropy,"C:/filepath/RecreationTourists_entropy.tif", overwrite=TRUE)

writeRaster(bnt10$Class,"C:/filepath/GeneticMedicalResources_class.tif", overwrite=TRUE)
writeRaster(bnt10$Entropy,"C:/filepath/GeneticMedicalResources_entropy.tif", overwrite=TRUE)

writeRaster(bnt11$Class,"C:/filepath/ReductionDamageInfraProperty_class.tif", overwrite=TRUE)
writeRaster(bnt11$Entropy,"C:/filepath/ReductionDamageInfraProperty_entropy.tif",
overwrite=TRUE)

writeRaster(bnt12$Class,"C:/filepath/WaterProvision_class.tif", overwrite=TRUE)
writeRaster(bnt12$Entropy,"C:/filepath/WaterProvision_entropy.tif", overwrite=TRUE)

writeRaster(bnt13$Class,"C:/filepath/PrimProd_class.tif", overwrite=TRUE)
writeRaster(bnt13$Entropy,"C:/filepath/PrimProd_entropy.tif", overwrite=TRUE)

#OUTPUT MAPS1
graphics.off()
par("mar")
par(mar=c(1,1,1,1))
par(mfrow=c(1,2))
plot(bnt8$Class, main='Most likely class')
plot(bnt8$Entropy, main='Uncertainty (Shannon index)')

#run the bnspatial for probability and target states
bn1 <- bnspatial(network, 'FoodProvMeat', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn1$Probability$High, main="Probability of High")
#plot(bn1$Probability$Medium, main="Probability of Medium")
#plot(bn1$Probability$Low, main="Probability of Low")
writeRaster(bn1$Probability$High,"C:/filepath/FoodProvMeat_high.tif", overwrite=TRUE)
writeRaster(bn1$Probability$Medium,"C:/filepath/FoodProvMeat_medium.tif", overwrite=TRUE)
```

```
writeRaster(bn1$Probability$Low,"C:/filepath/FoodProvMeat_low.tif", overwrite=TRUE)

bn2 <- bnspatial(network, 'FoodProvVeg', spatialData, intervals_lk, msk=a_raster, what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn2$Probability$High, main="Probability of High")
#plot(bn2Probability$Medium, main="Probability of Medium")
#plot(bn2$Probability$Low, main="Probability of Low")
writeRaster(bn2$Probability$High,"C:/filepath/FoodProvVeg_high.tif", overwrite=TRUE)
writeRaster(bn2$Probability$Medium,"C:/filepath/FoodProvVeg_medium.tif", overwrite=TRUE)
writeRaster(bn2$Probability$Low,"C:/filepath/FoodProvVeg_low.tif", overwrite=TRUE)

bn3 <- bnspatial(network, 'CarbonSequestration', spatialData, intervals_lk, msk=a_raster, what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn3$Probability$High, main="Probability of High")
#plot(bn3$Probability$Medium, main="Probability of Medium")

writeRaster(bn3$Probability$High,"C:/filepath/CarbonSequestration_high.tif", overwrite=TRUE)
writeRaster(bn3$Probability$Medium,"C:/filepath/CarbonSequestration_medium.tif",
overwrite=TRUE)
writeRaster(bn3$Probability$Low,"C:/filepath/CarbonSequestration_low.tif", overwrite=TRUE)

bn4 <- bnspatial(network, 'Coffee', spatialData, intervals_lk, msk=a_raster, what="probability", targetState=c("High","Medium","Low"))

#par(mfrow=c(1,2))
#plot(bn4$Probability$High, main="Probability of High")
#plot(bn4$Probability$Medium, main="Probability of Medium")

writeRaster(bn4$Probability$High,"C:/filepath/Coffee_high.tif", overwrite=TRUE)
writeRaster(bn4$Probability$Medium,"C:/filepath/Coffee_medium.tif", overwrite=TRUE)
writeRaster(bn4$Probability$Low,"C:/filepath/Coffee_low.tif", overwrite=TRUE)

bn5 <- bnspatial(network, 'Honey', spatialData, intervals_lk, msk=a_raster, what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn5$Probability$High, main="Probability of High")
#plot(bn5$Probability$Medium, main="Probability of Medium")

writeRaster(bn5$Probability$High,"C:/filepath/Honey_high.tif", overwrite=TRUE)
writeRaster(bn5$Probability$Medium,"C:/filepath/Honey_medium.tif", overwrite=TRUE)
writeRaster(bn5$Probability$Low,"C:/filepath/Honey_low.tif", overwrite=TRUE)

bn6 <- bnspatial(network, 'Fuel', spatialData, intervals_lk, msk=a_raster, what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn6$Probability$High, main="Probability of High")
```

```
#plot(bn6$Probability$Medium, main="Probability of Medium")

writeRaster(bn6$Probability$High,"C:/filepath/Fuel_high.tif", overwrite=TRUE)
writeRaster(bn6$Probability$Medium,"C:/filepath/Fuel_medium.tif", overwrite=TRUE)
writeRaster(bn6$Probability$Low,"C:/filepath/Fuel_low.tif", overwrite=TRUE)

bn7 <- bnspatial(network, 'ConstructionMaterials', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn7$Probability$High, main="Probability of High")
#plot(bn7$Probability$Low, main="Probability of Low")

writeRaster(bn7$Probability$High,"C:/filepath/ConstructionMaterials_high.tif", overwrite=TRUE)
writeRaster(bn7$Probability$Medium,"C:/filepath/ConstructionMaterials_medium.tif",
overwrite=TRUE)
writeRaster(bn7$Probability$Low,"C:/filepath/ConstructionMaterials_low.tif", overwrite=TRUE)

bn8 <- bnspatial(network, 'RecreationLocal', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn8$Probability$High, main="Probability of High")
#plot(bn8$Probability$Low, main="Probability of Low")

writeRaster(bn8$Probability$High,"C:/filepath/RecreationLocal_high.tif", overwrite=TRUE)
writeRaster(bn8$Probability$Medium,"C:/filepath/RecreationLocal_medium.tif", overwrite=TRUE)
writeRaster(bn8$Probability$Low,"C:/filepath/RecreationLocal_low.tif", overwrite=TRUE)

bn9 <- bnspatial(network, 'RecreationTourists', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn9$Probability$High, main="Probability of High")
#plot(bn9$Probability$Medium, main="Probability of Medium")

writeRaster(bn9$Probability$High,"C:/filepath/RecreationTourists_high.tif", overwrite=TRUE)
writeRaster(bn9$Probability$Medium,"C:/filepath/RecreationTourists_medium.tif",
overwrite=TRUE)
writeRaster(bn9$Probability$Low,"C:/filepath/RecreationTourists_low.tif", overwrite=TRUE)

bn10 <- bnspatial(network, 'GeneticMedicalResources', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn10$Probability$High, main="Probability of High")
#plot(bn10$Probability$Medium, main="Probability of Medium")

writeRaster(bn10$Probability$High,"C:/filepath/GeneticMedicalResources_high.tif",
overwrite=TRUE)
writeRaster(bn10$Probability$Medium,"C:/filepath/GeneticMedicalResources_medium.tif",
overwrite=TRUE)
```

```
writeRaster(bn10$Probability$Low,"C:/filepath/GeneticMedicalResources_low.tif", overwrite=TRUE)

bn11 <- bnspatial(network, 'ReductionDamageInfraProperty', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn11$Probability$High, main="Probability of High")
#plot(bn11$Probability$Medium, main="Probability of Medium")

writeRaster(bn11$Probability$High,"C:/filepath/ReductionDamageInfraProperty_high.tif",
overwrite=TRUE)
writeRaster(bn11$Probability$Medium,"C:/filepath/ReductionDamageInfraProperty_medium.tif",
overwrite=TRUE)
writeRaster(bn11$Probability$Low,"C:/filepath/ReductionDamageInfraProperty_low.tif",
overwrite=TRUE)

bn12 <- bnspatial(network, 'WaterProvision', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn12$Probability$High, main="Probability of High")
#plot(bn12$Probability$Medium, main="Probability of Medium")

writeRaster(bn12$Probability$High,"C:/filepath/WaterProvision_high.tif", overwrite=TRUE)
writeRaster(bn12$Probability$Medium,"C:/filepath/WaterProvision_medium.tif", overwrite=TRUE)
writeRaster(bn12$Probability$Low,"C:/filepath/WaterProvision_low.tif", overwrite=TRUE)

bn13 <- bnspatial(network, 'PrimProdInputs', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn13$Probability$High, main="Probability of High")
#plot(bn13$Probability$Medium, main="Probability of Medium")

writeRaster(bn13$Probability$High,"C:/filepath/PrimProd_high.tif", overwrite=TRUE)
writeRaster(bn13$Probability$Medium,"C:/filepath/PrimProd_medium.tif", overwrite=TRUE)
writeRaster(bn13$Probability$Low,"C:/filepath/PrimProd_low.tif", overwrite=TRUE)

#addtional network target
target14 <- 'CleanWaterDrinking'
bnt14 <- bnspatial(network, target13, spatialData, intervals_lk, msk=a_raster)

writeRaster(bnt14$Class,"C:/filepath/ClWaterDrink_class.tif", overwrite=TRUE)
writeRaster(bnt14$Entropy,"C:/filepath/ClWaterDrink_entropy.tif", overwrite=TRUE)

bn14 <- bnspatial(network, 'CleanWaterDrinking', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))
#par(mfrow=c(1,2))
#plot(bn14$Probability$High, main="Probability of High")
#plot(bn14$Probability$Medium, main="Probability of Medium")
```

```
writeRaster(bn14$Probability$High,"C:/filepath/ClWaterDrink_high.tif", overwrite=TRUE)
writeRaster(bn14$Probability$Medium,"C:/filepath/ClWaterDrink_medium.tif", overwrite=TRUE)
writeRaster(bn14$Probability$Low,"C:/filepath/ClWaterDrink_low.tif", overwrite=TRUE)
```

Annex 3: Sample R code of scenario analysis

An example of the additional R code for the expanded BN model used for the scenario analysis is provided below. In total the model had an additional 28 target nodes for the scenario analysis, the first two are presented here to indicate the code used.

```
#set the targets for the scenario
target_s1 <-'ArableHortExp'
target_s2 <- 'CoffeeExp'

#calculate scenarios
bn_sce1 <- bnspatial(networkscenario, target_s1, spatialData, intervals_lk, msk=a_raster)

writeRaster(bn_sce1$Class,"C:/filepath/ArableHortExp_class.tif", overwrite=TRUE)
writeRaster(bn_sce1$Entropy,"C:/filepath/ArableHortExp_entropy.tif", overwrite=TRUE)

bn_sce1p <- bnspatial(networkscenario, 'ArableHortExp', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))

writeRaster(bn_sce1p$Probability$High,"C:/filepath/ArableHortExp_high.tif", overwrite=TRUE)
writeRaster(bn_sce1p$Probability$Medium,"C:/filepath/ArableHortExp_medium.tif",
overwrite=TRUE)
writeRaster(bn_sce1p$Probability$Low,"C:/filepath/ArableHortExp_low.tif", overwrite=TRUE)


bn_sce2 <- bnspatial(networkscenario, target_s2, spatialData, intervals_lk, msk=a_raster)
writeRaster(bn_sce2$Class,"C:/filepath/CoffeeExp_class.tif", overwrite=TRUE)
writeRaster(bn_sce2$Entropy,"C:/filepath/CoffeeExp_entropy.tif", overwrite=TRUE)

bn_sce2p <- bnspatial(networkscenario, 'CoffeeExp', spatialData, intervals_lk, msk=a_raster,
what="probability", targetState=c("High","Medium","Low"))

writeRaster(bn_sce2p$Probability$High,"C:/filepath/CoffeeExp_high.tif", overwrite=TRUE)
writeRaster(bn_sce2p$Probability$Medium,"C:/filepath/CoffeeExp_medium.tif", overwrite=TRUE)
writeRaster(bn_sce2p$Probability$Low,"C:/filepath/CoffeeExp_low.tif", overwrite=TRUE)
```